Achieving the mid-high end of the LISA sensitivity band with the LISA short arm
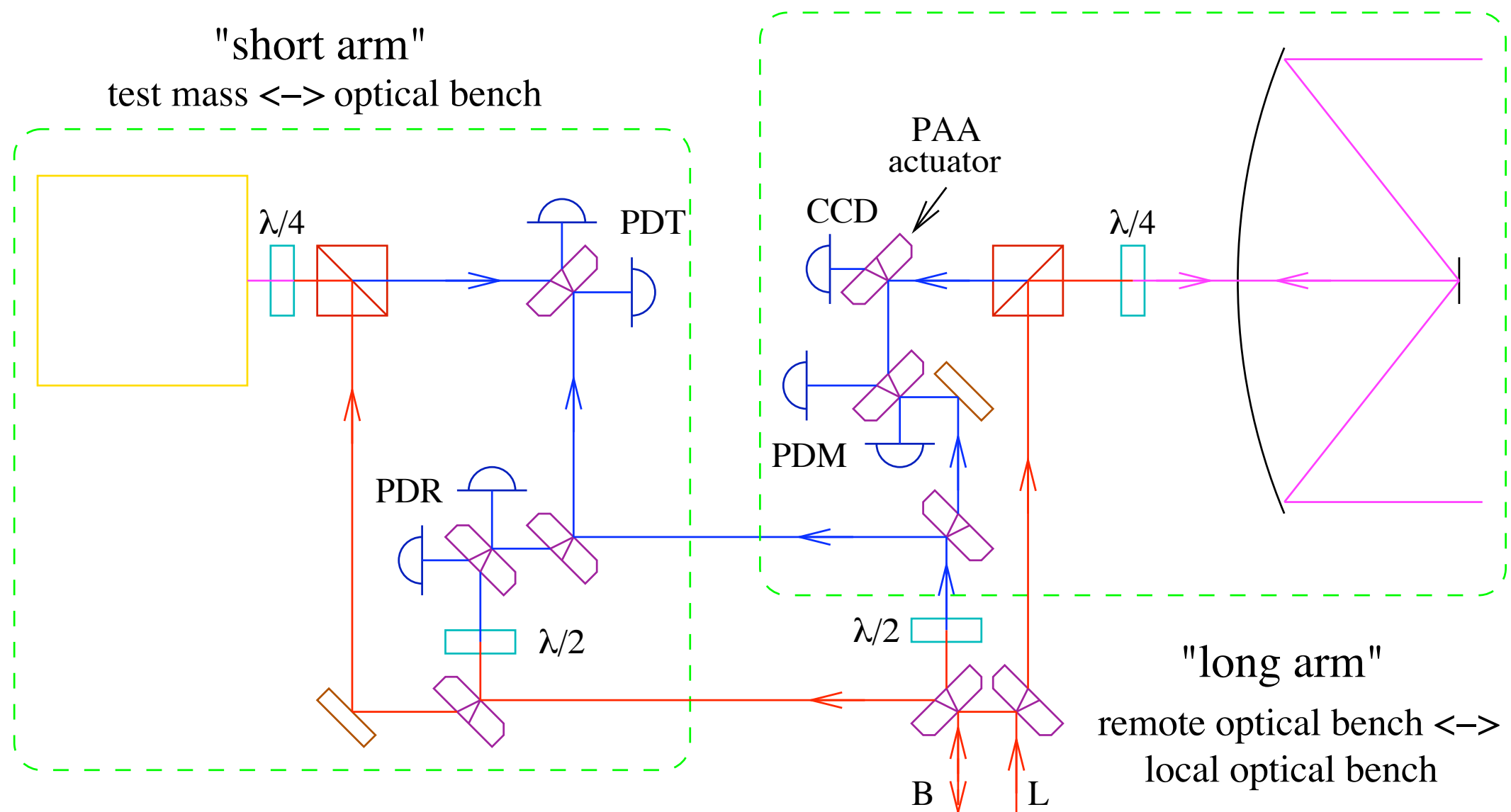

optical bench

optical bench

d_{12}

5 million km

test mass

d_1

d_2

test mass

$$L_{12} = d_1 + d_2 + d_{12}$$
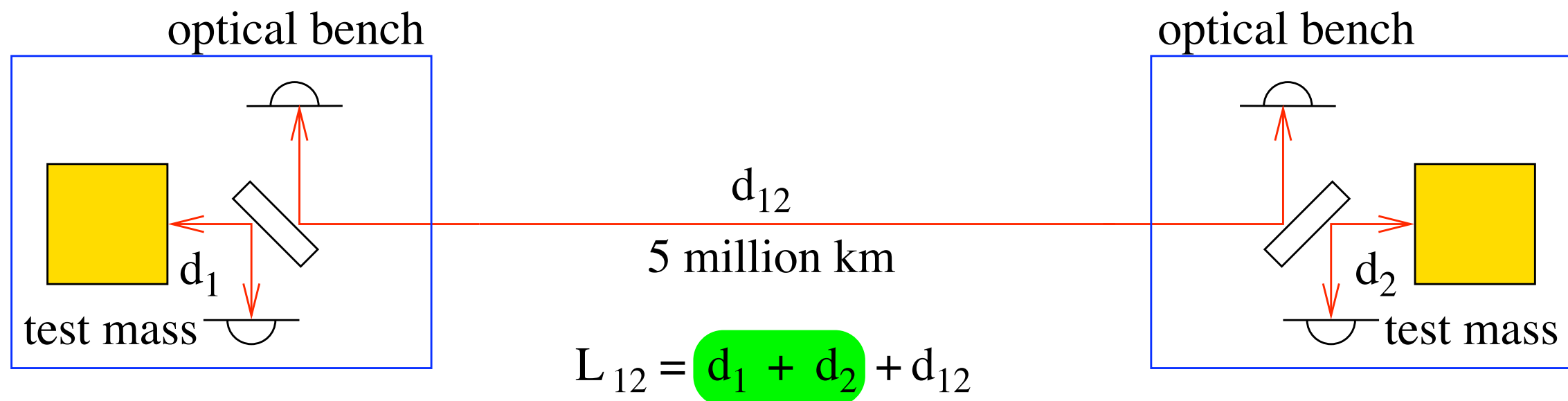
Gerhard Heinzel,

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Hannover.

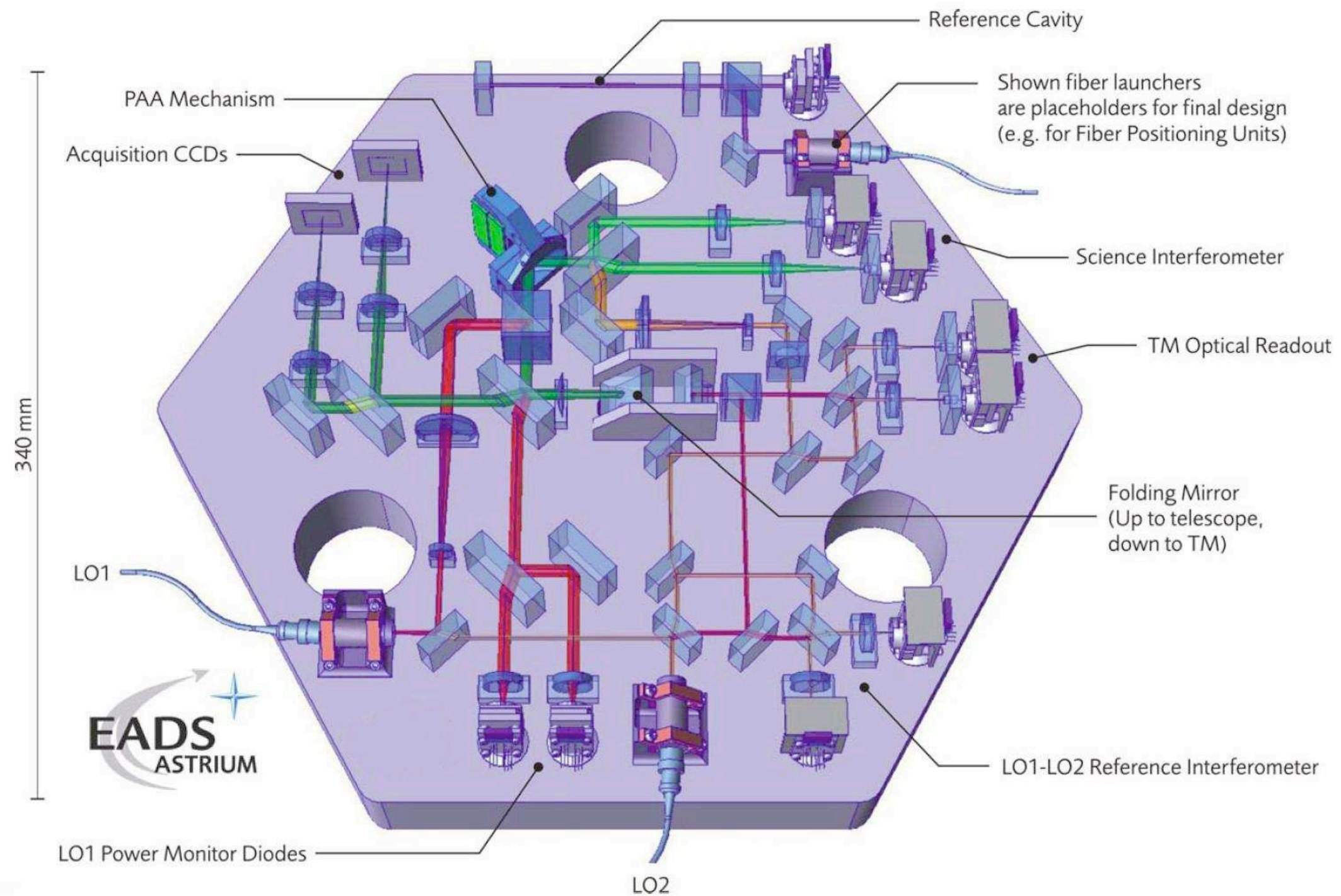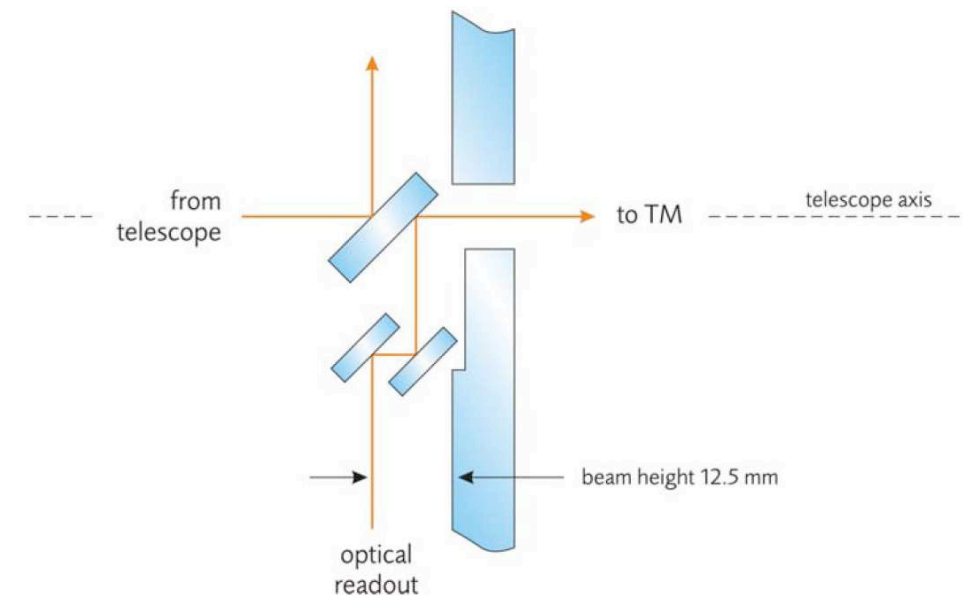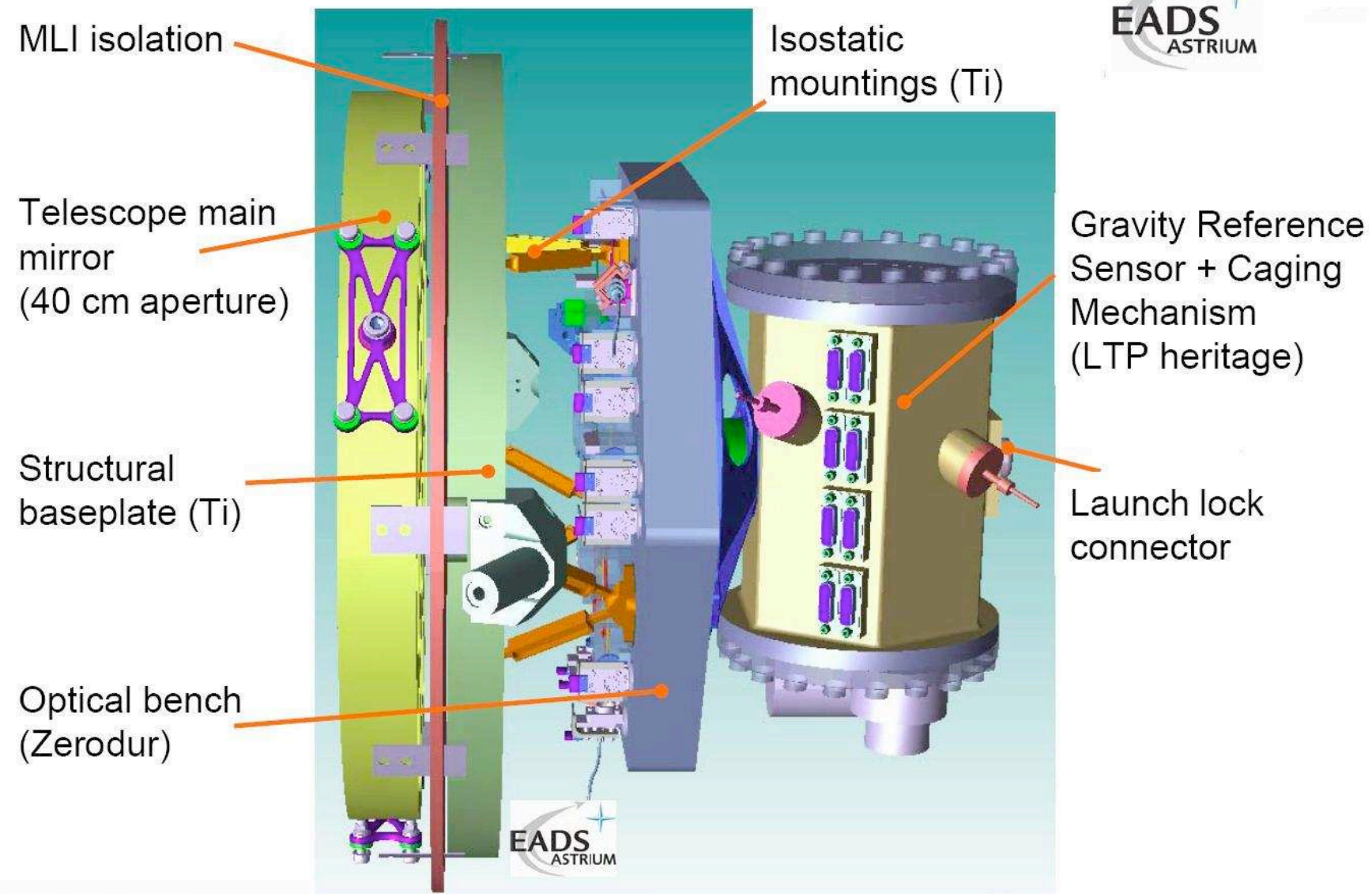**6th International LISA symposium, GSFC, June 21, 2006.**

Optical bench

"short arm"
test mass <-> optical bench

λ/4   PDT
       PDR
λ/2

PAA
actuator
CCD   λ/4
PDM
λ/2

B   L

"long arm"
remote optical bench <->
local optical bench

Optical bench

Reference Cavity

Shown fiber launchers
are placeholders for final design
(e.g. for Fiber Positioning Units)

PAA Mechanism

Acquisition CCDs

Science Interferometer

TM Optical Readout

Folding Mirror
(Up to telescope,
down to TM)

LO1

340 mm

EADS ASTRIUM

LO1-LO2 Reference Interferometer

LO1 Power Monitor Diodes

LO2

LISA Optical Assembly - Core Elements

MLI isolation

Telescope main mirror (40 cm aperture)

Structural baseplate (Ti)

Optical bench (Zerodur)

Isostatic mountings (Ti)

EADS ASTRIUM

Gravity Reference Sensor + Caging Mechanism (LTP heritage)

Launch lock connector

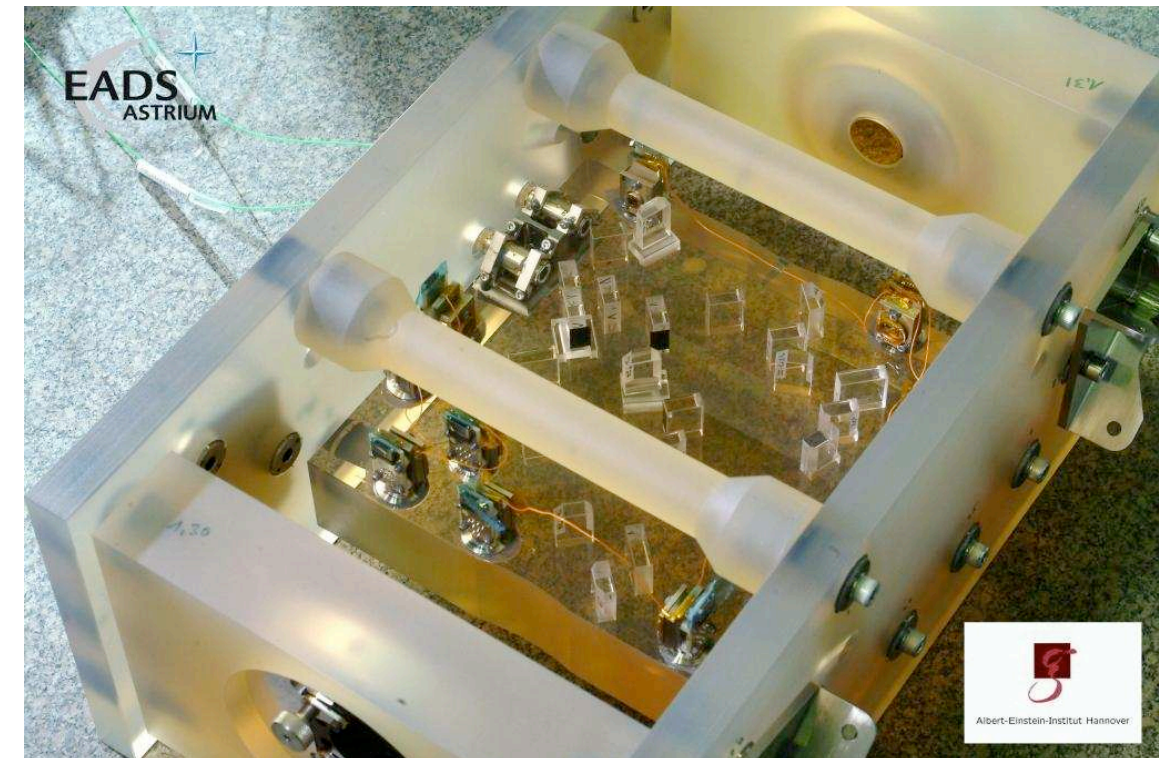EADS ASTRIUM

from telescope

to TM

telescope axis
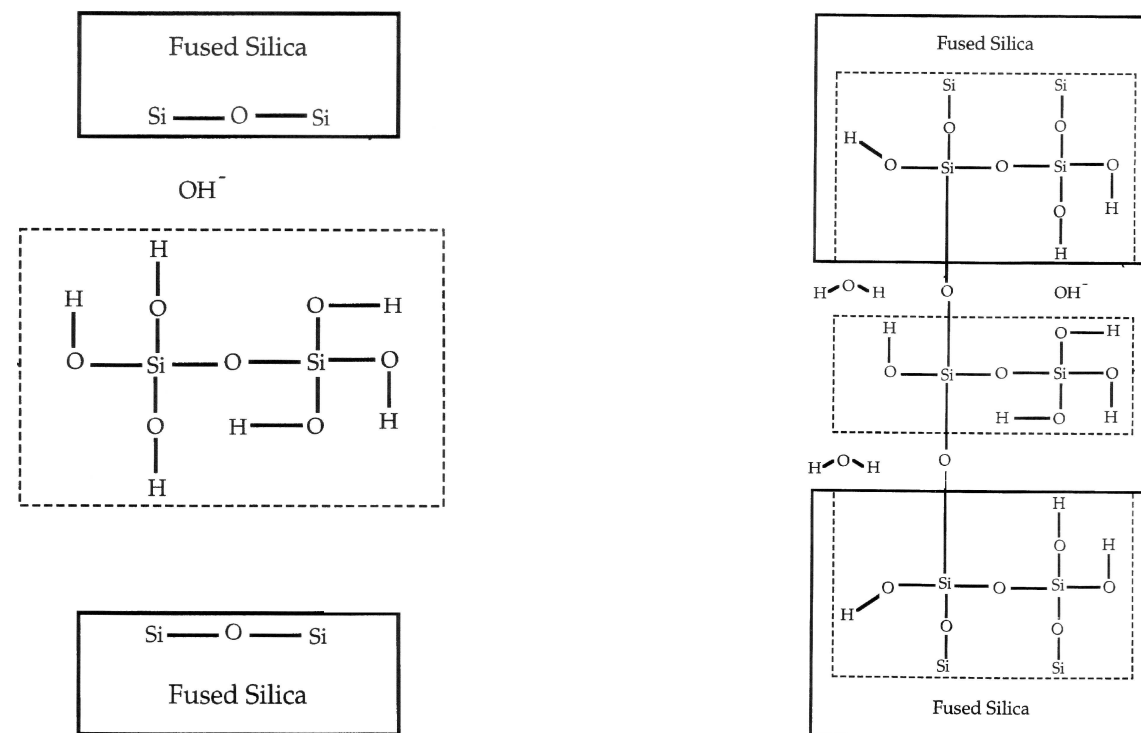
optical readout

beam height 12.5 mm

see talk by U. Johann this afternoon!

Hydroxycatalysis bonding ('Silicate bonding')

Silicate bonding was developed by Stanford for GP/B and further developed by Glasgow.

Using a catalyst (potassium hydroxide or sodium silicate solution), a quasi-monolithic bond is formed between polished and cleaned surfaces of glass, certain ceramics, or even some metals.

The bond is extremely thin, tough and stable.

Will be flown on LPF!
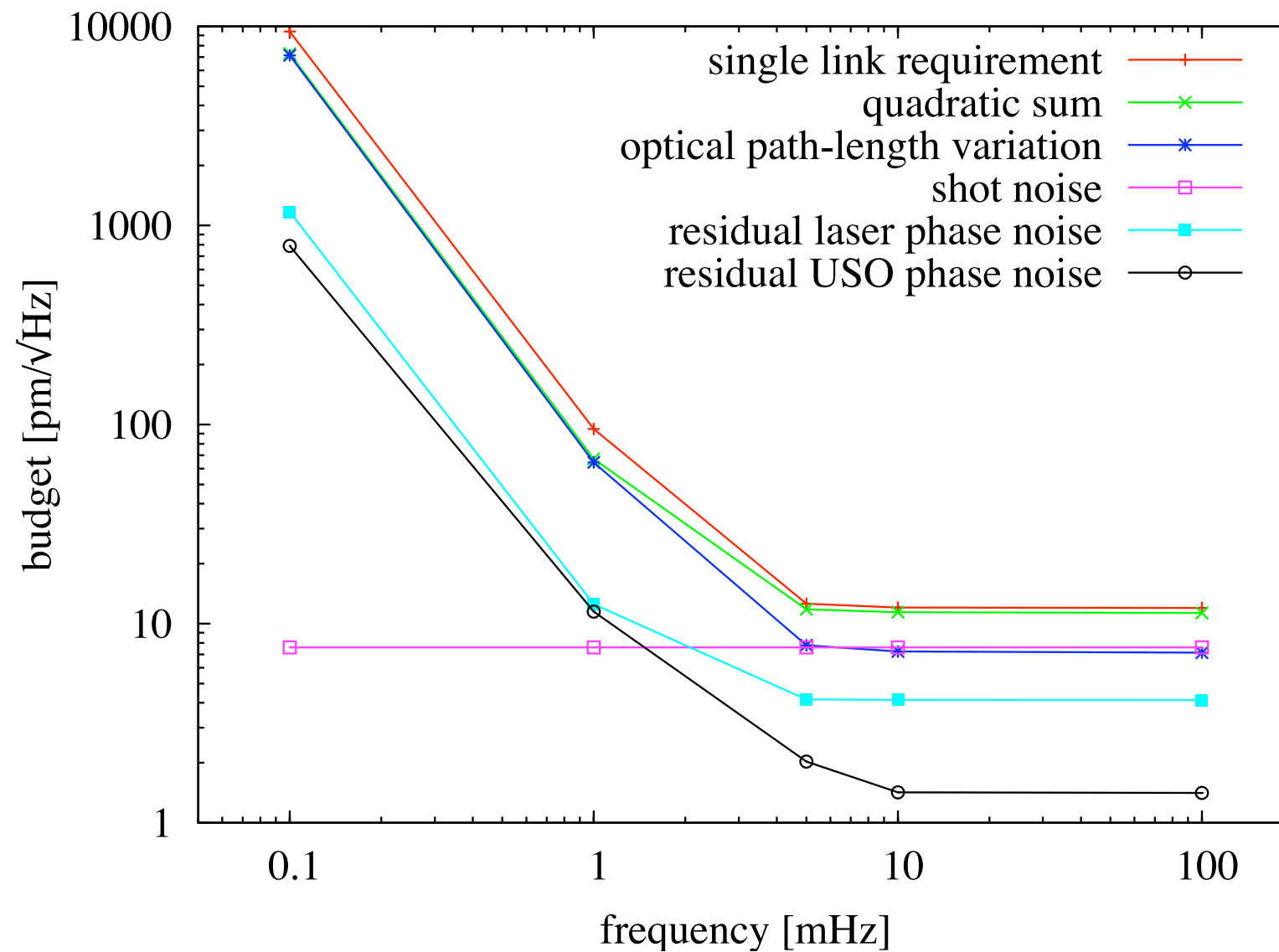**see talk by D. Robertson / C. Killow this afternoon!**

Requirement breakdown

dominant noise sources:
$< 5\,\mathrm{mHz}$: acceleration noise $3 \cdot 10^{-15}\,\mathrm{ms^{-2}}/\sqrt{\mathrm{Hz}}$
$> 5\,\mathrm{mHz}$: **optical metrology** $12\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ for single link

budgets at $100\,\mathrm{mHz}$ $[\mathrm{pm}/\sqrt{\mathrm{Hz}}]$:
7.6 shot noise,
7.2 optical path-length variation,
4.1 residual laser phase noise,
1.4 residual USO phase noise.

Shot noise

Budget at 100 mHz: $7.5\,\text{pm}/\sqrt{\text{Hz}}$ real shot noise on long arm, corresponding to a useful received optical power of

$$P = \frac{\hbar\, c\, \lambda}{2\pi\, \tilde{x}^2} = 95\,\text{pW}.$$

The contributions of electronic noise must be negligible.
This concerns mainly the photodiode preamplifier.

With 1 mW of LO and the signal split in 8 quadrant channels, the resulting signal currents are:

$70\,\mu\text{A}$ DC photocurrent,
44 nA signal (amplitude),
$4.7\,\text{pA}/\sqrt{\text{Hz}}$ shot noise.

Both shot noise and signal increase in parallel with $\sqrt{\text{LO power}}$

The photodiode-preamplifier combination must have:

− bandwidth from 2 MHz to 20 MHz (minimum),
− electronic noise considerably smaller than $4.7\,\text{pA}/\sqrt{\text{Hz}}$,
− low power dissipation,
− small phase shift vs. temperature etc.,
− very constant bias voltage across the photodiode.

Photodiode preamplifiers

Many standard approaches (resistive load, op-amp transimpedance amplifier, impedance matching) seem difficult. Best candidate in simulations: discrete design with GHz transistors. It seems possible to reach $2.5\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$, but not $1\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$.
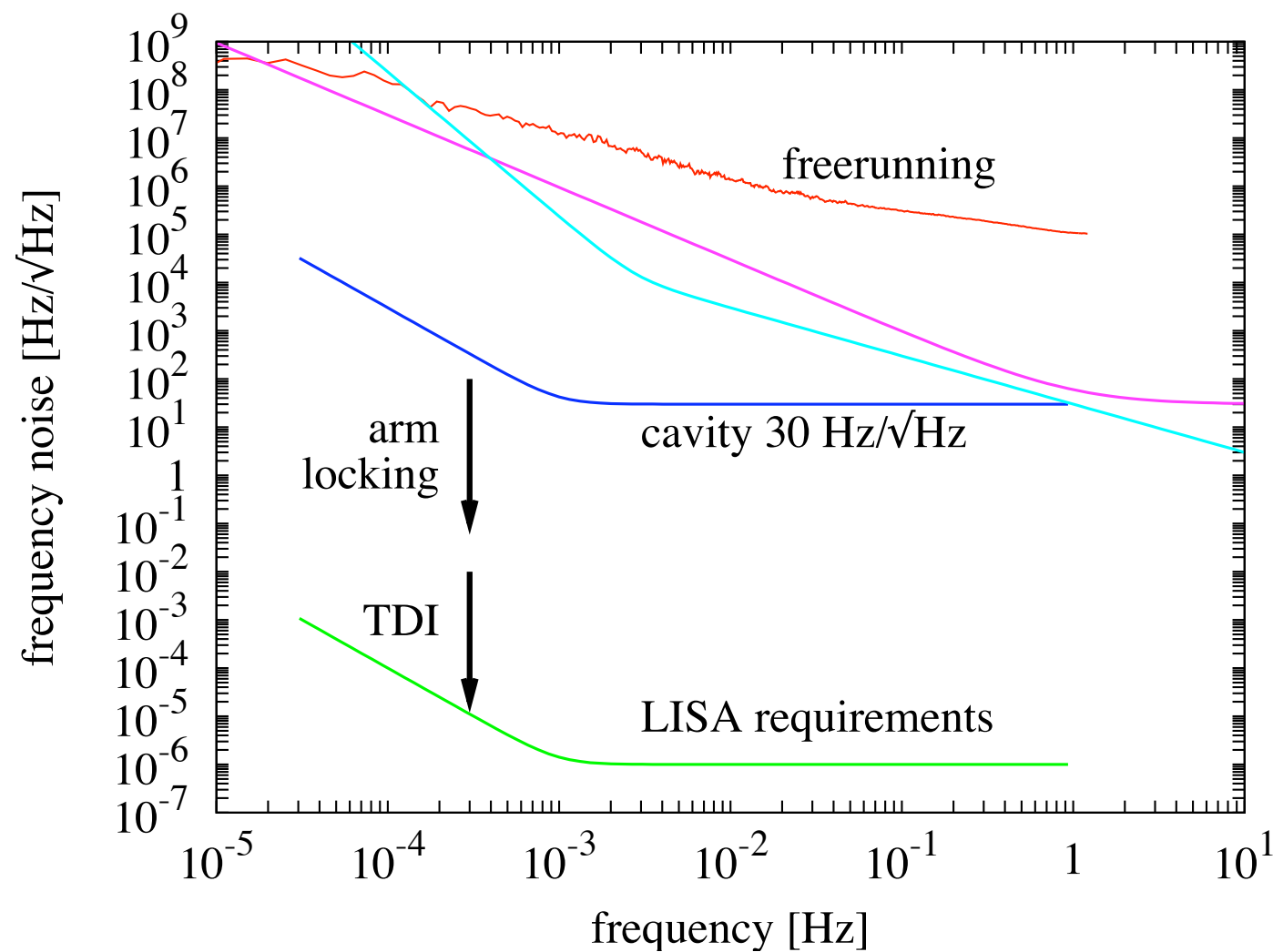

influence of 2.5 pA/√Hz preamp noise
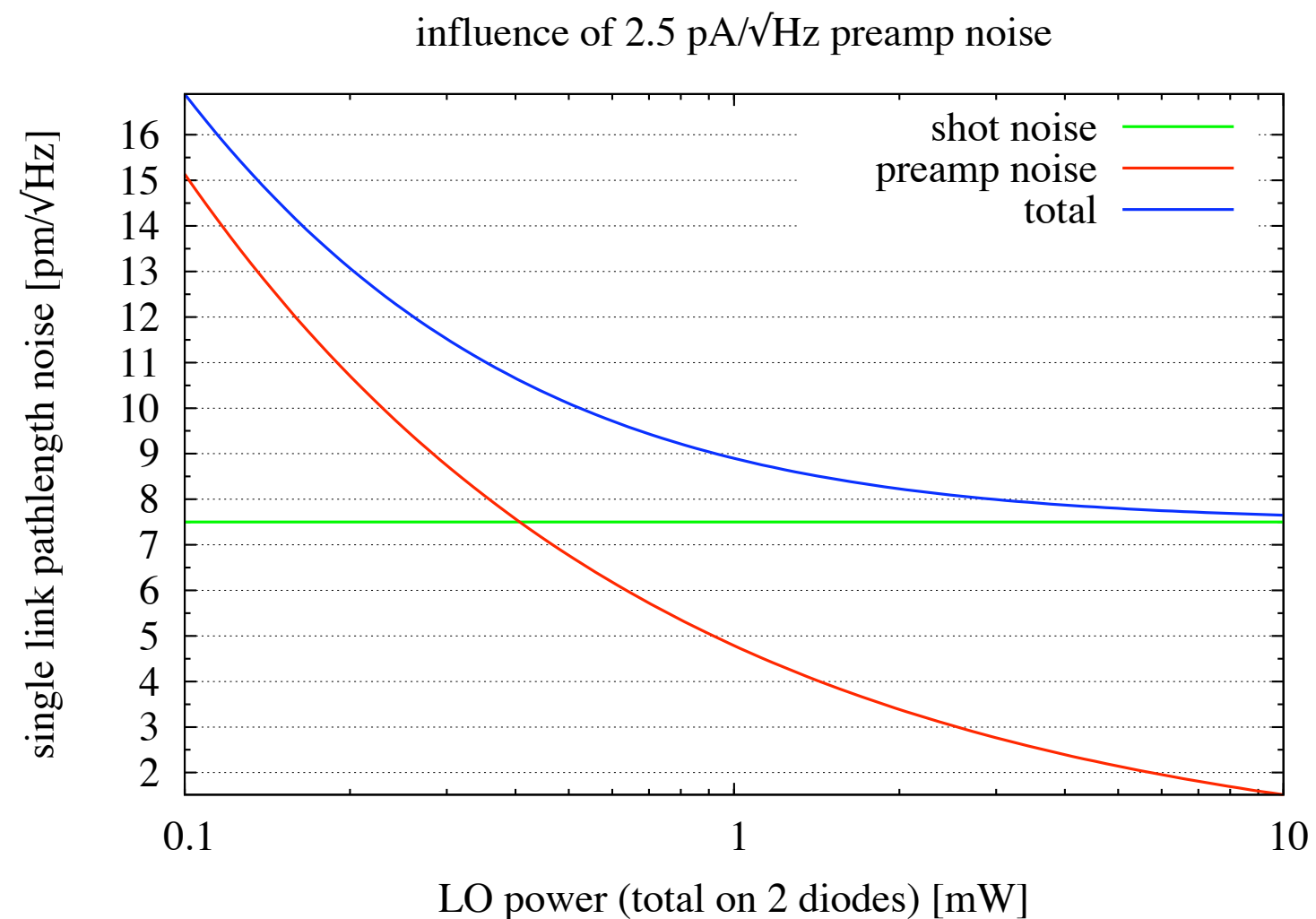
The main troublemaker is the photodiode capacitance.

Laser frequency stabilization

3-step approach:

1) cavity prestabilization achieves $10 \ldots 1000 \, \mathrm{Hz}/\sqrt{\mathrm{Hz}}$

missing $8 \ldots 9$ orders of magnitude

2) arm locking *

3) time-delay interferometry (TDI) *

*: see next talk by Daniel Shaddock

resent results suggest that the low frequency range can be handled by arm-locking, while the frequencies $> 1 \, \mathrm{Hz}$ are important for the phasemeter.

frequency plan
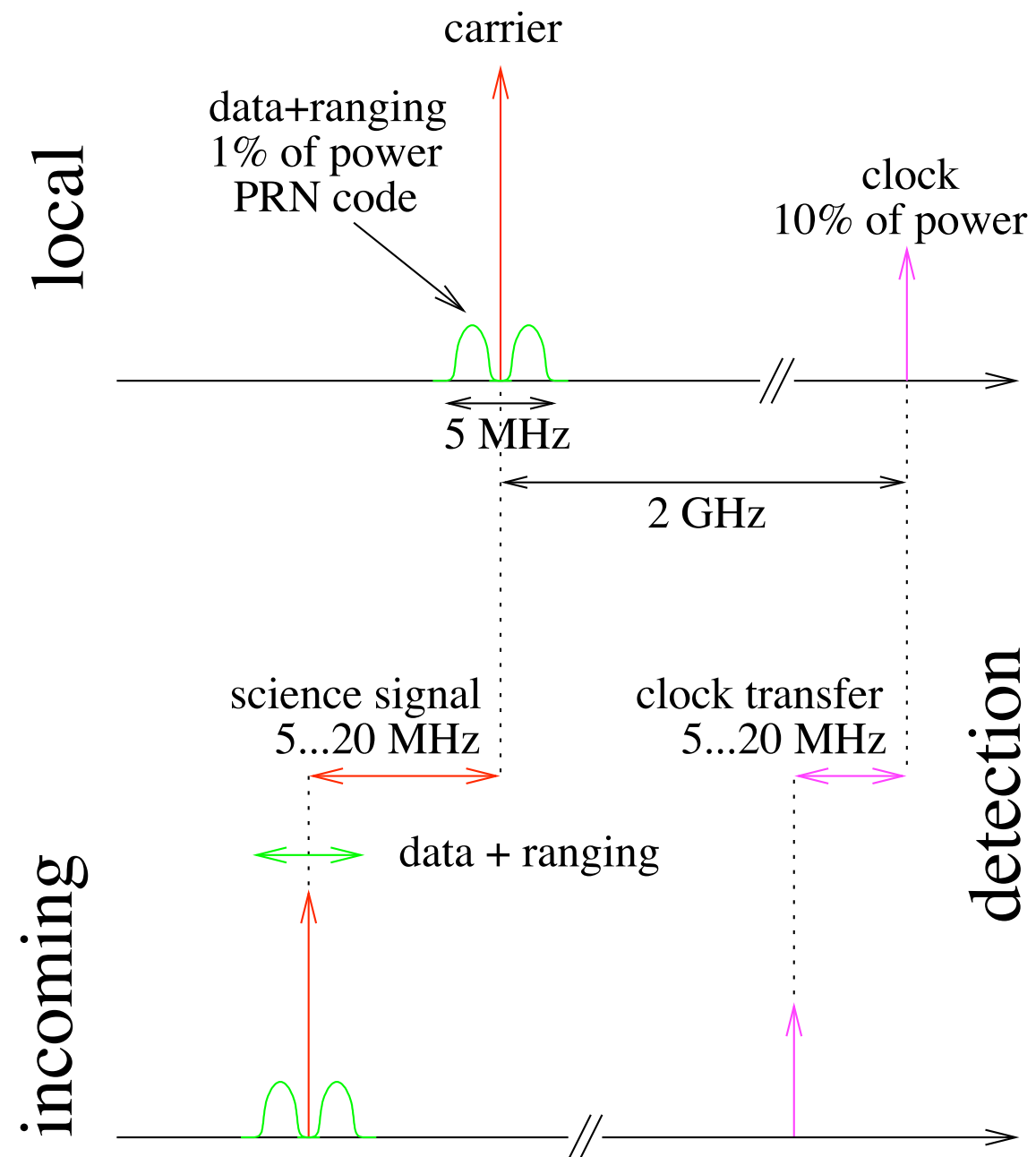
phase measurement of carrier − carrier beat
provides main science signal

orthogonal pseudo-random codes (PRN) for data
transfer. ranging comes as cheap by-product

clock transfer via sideband − sideband beat
see talk by B. Klipstein this afternoon

occasional frequency switching keeps all beatnotes
in the range 5. . . 20 MHz

frequency swapping

backscatter (mW) f1

100 pW f2

$\lambda/4$

LO 3mW f3

1W f1
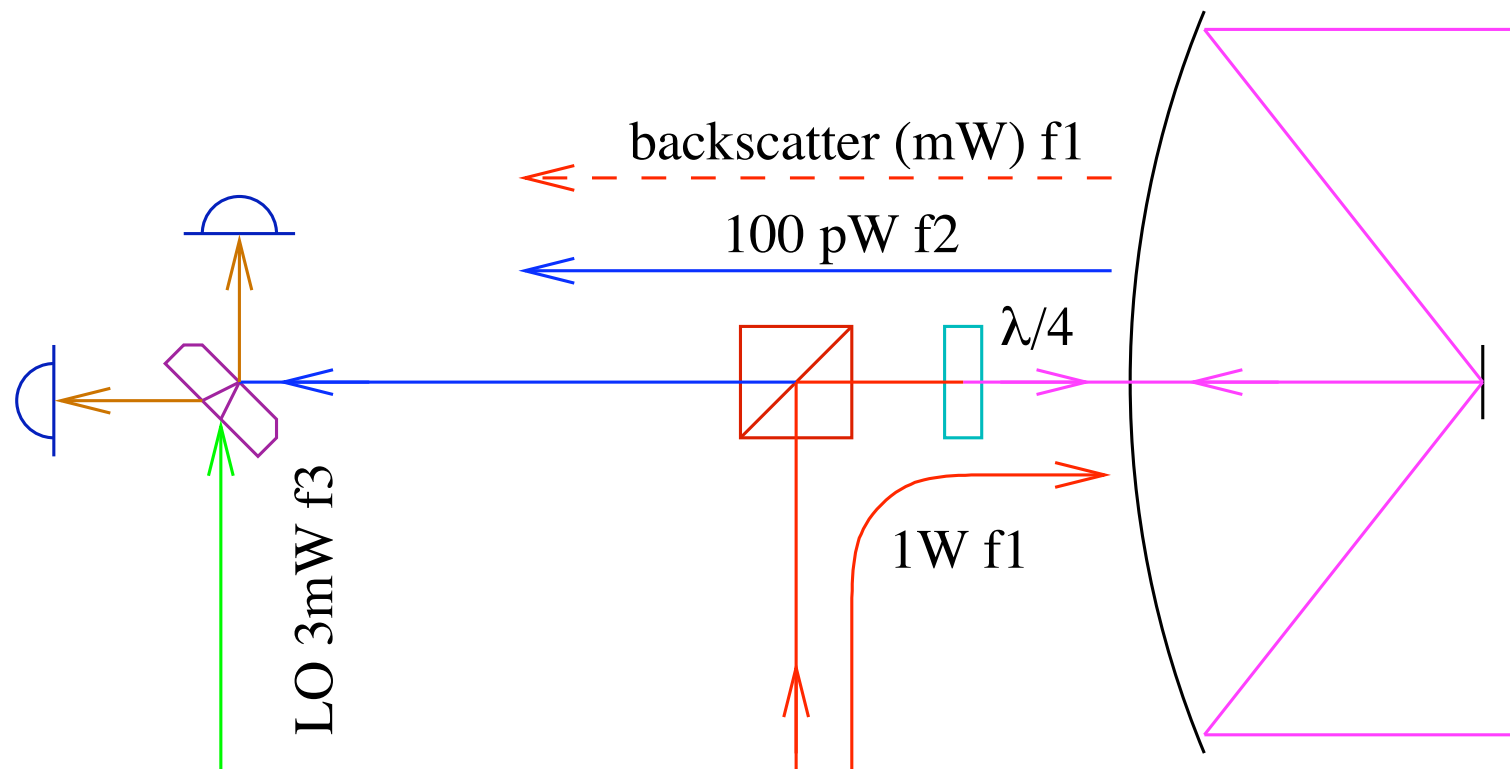
Old layouts used the outgoing laser (f_1) also as local oscillator (LO) for the incoming light. Any backscatter would thus add to the LO with uncontrolled phase.

Frequency swapping uses a different frequency (f_3) as LO, such that the signal at $|f_2 - f_3|$ is at a different frequency from the backscatter beat $|f_1 - f_3|$. The different frequency can conveniently be obtained from the second laser (mainly serving the second OB).

frequency swapping
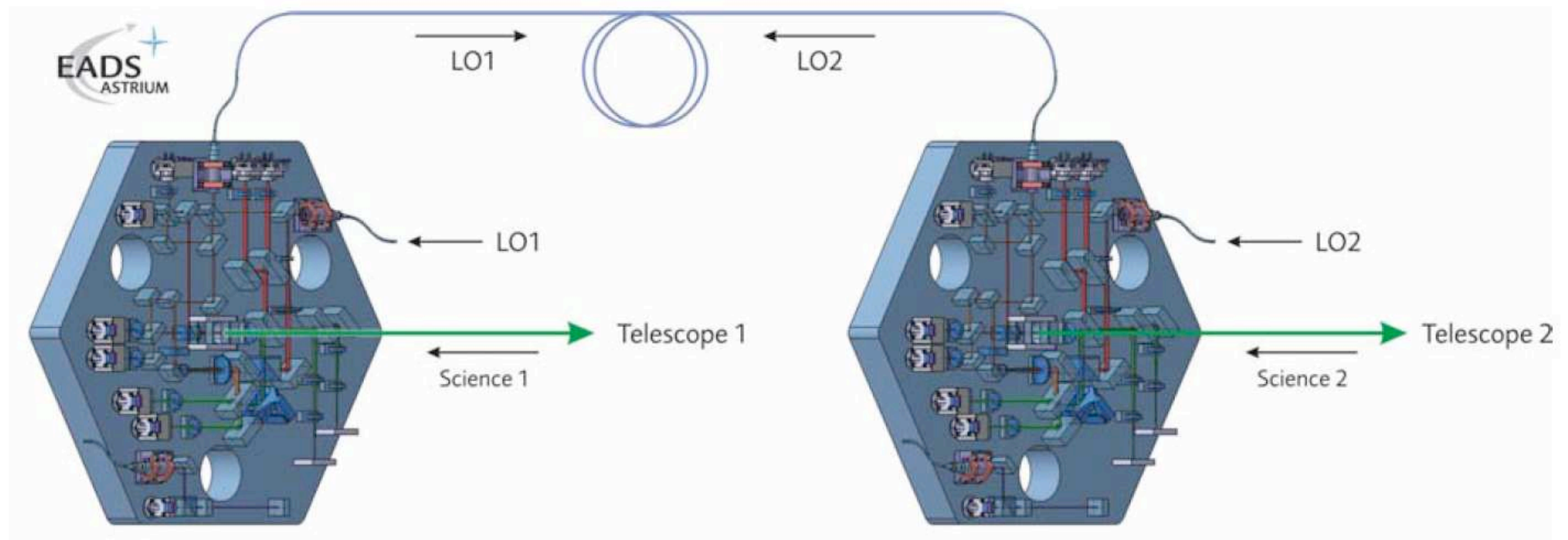
The LO light is exchanged between the two optical benches with one single-mode PM fiber used bidirectionally in the same polarization state. The phase shift in both directions must be the same to μrad (pm) level. Laboratory experiments to verify this assumption are under way.

Laser system
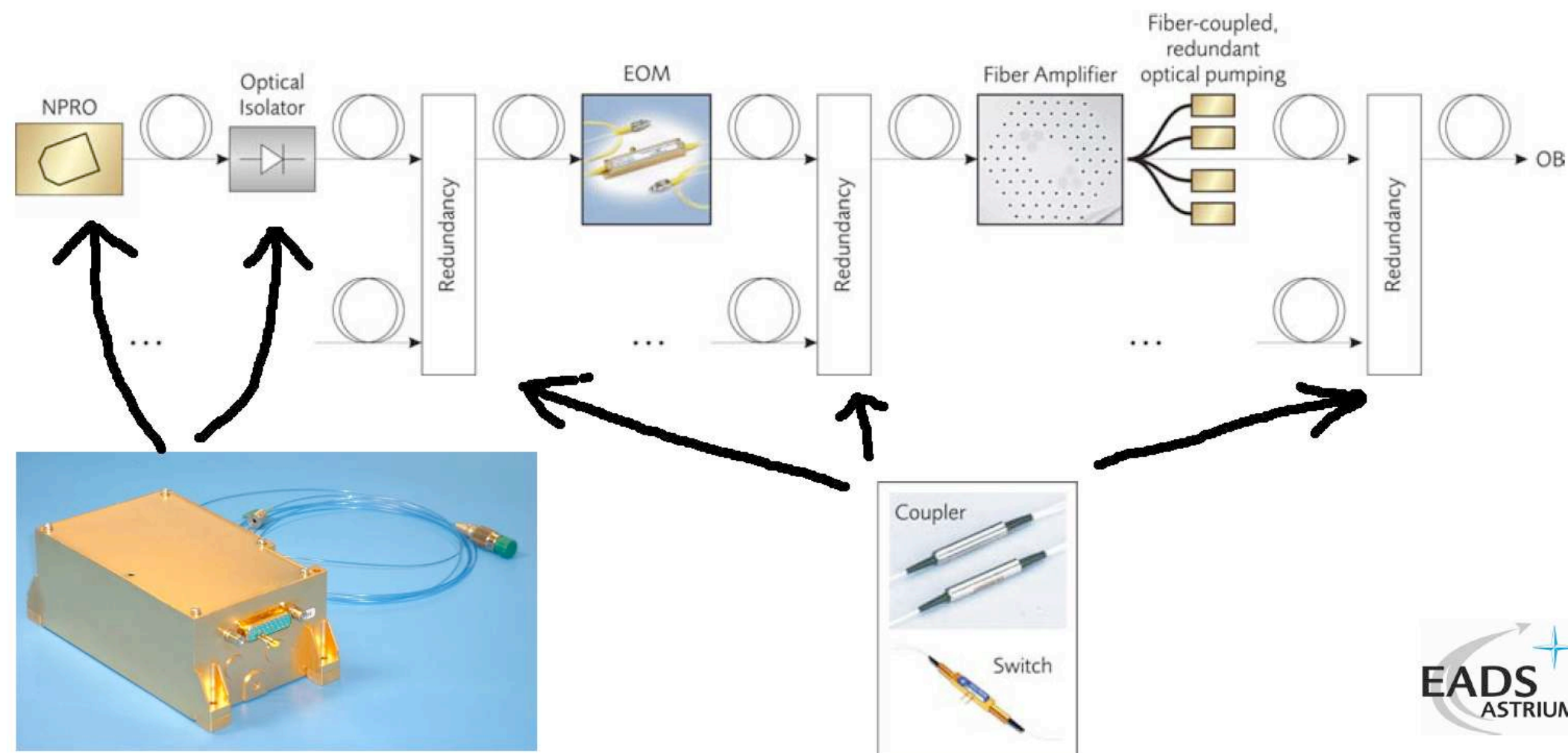
There are several possible candidates for the LISA laser. One is a seed NPRO (the LPF laser), a fiber-coupled EOM and a fiber amplifier.

Important requirements are:
− reliability, long life and space qualification,
− phase fidelity of the 2 GHz sidebands from applied electrical signal to outgoing light measurements are ongoing, see also **talk by B. Klipstein this afternoon**

Laser tests: sideband phase fidelity

Any differential phase noise between carrier and 2 GHz sideband that is produced in the EOM or in the laser amplifier will contribute to the clock noise. No practical way to measure this noise in LISA is known. Hence we have to rely on high intrinsic phase stability (low dispersion).
We are building laboratory test setups:
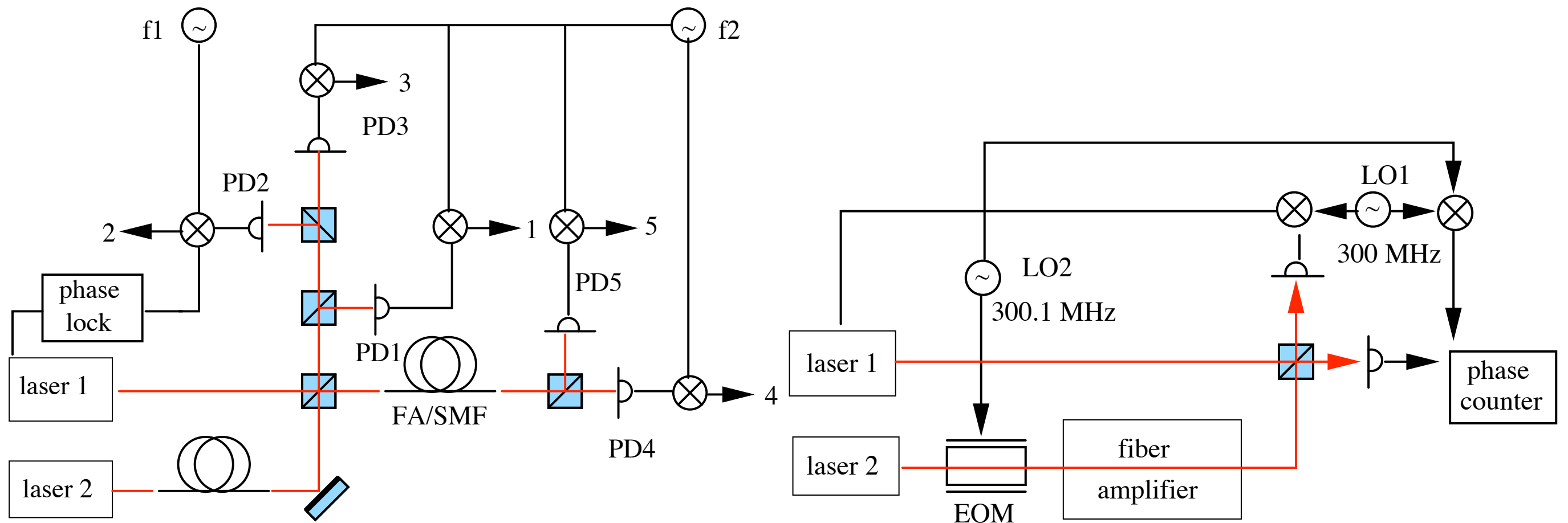
The setups so far achieve $\approx$ mrad/$\sqrt{\text{Hz}}$ sensitivities. First results are non-conclusive, and further investigations are ongoing.

Phasemeter

Digital PLL tracks carrier–carrier beat

fast ADC (60...80 MHz)

DPLL in FPGA/ASIC

phase output from phase accumulator

residual phase difference fed to PRN demodulator
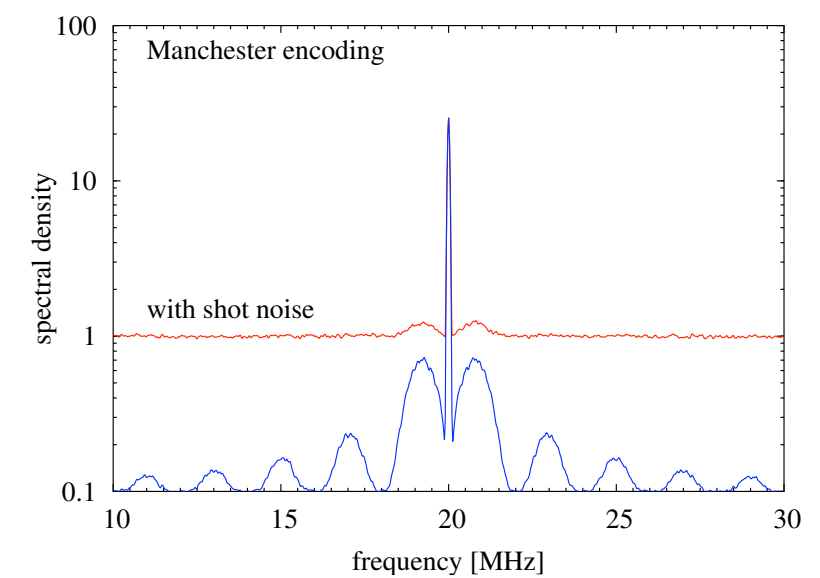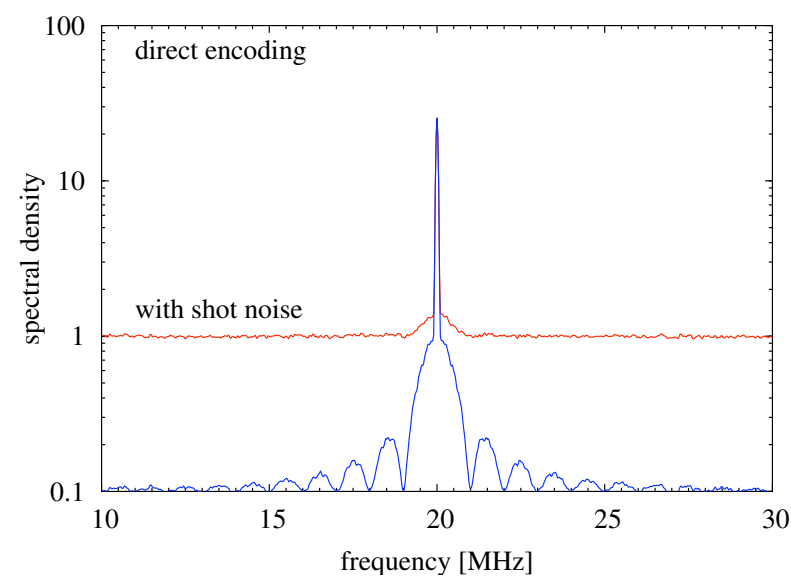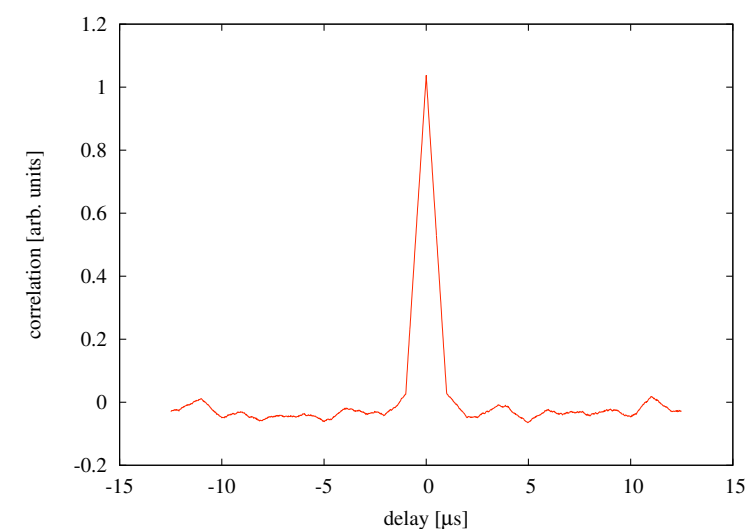
see two talks on friday.
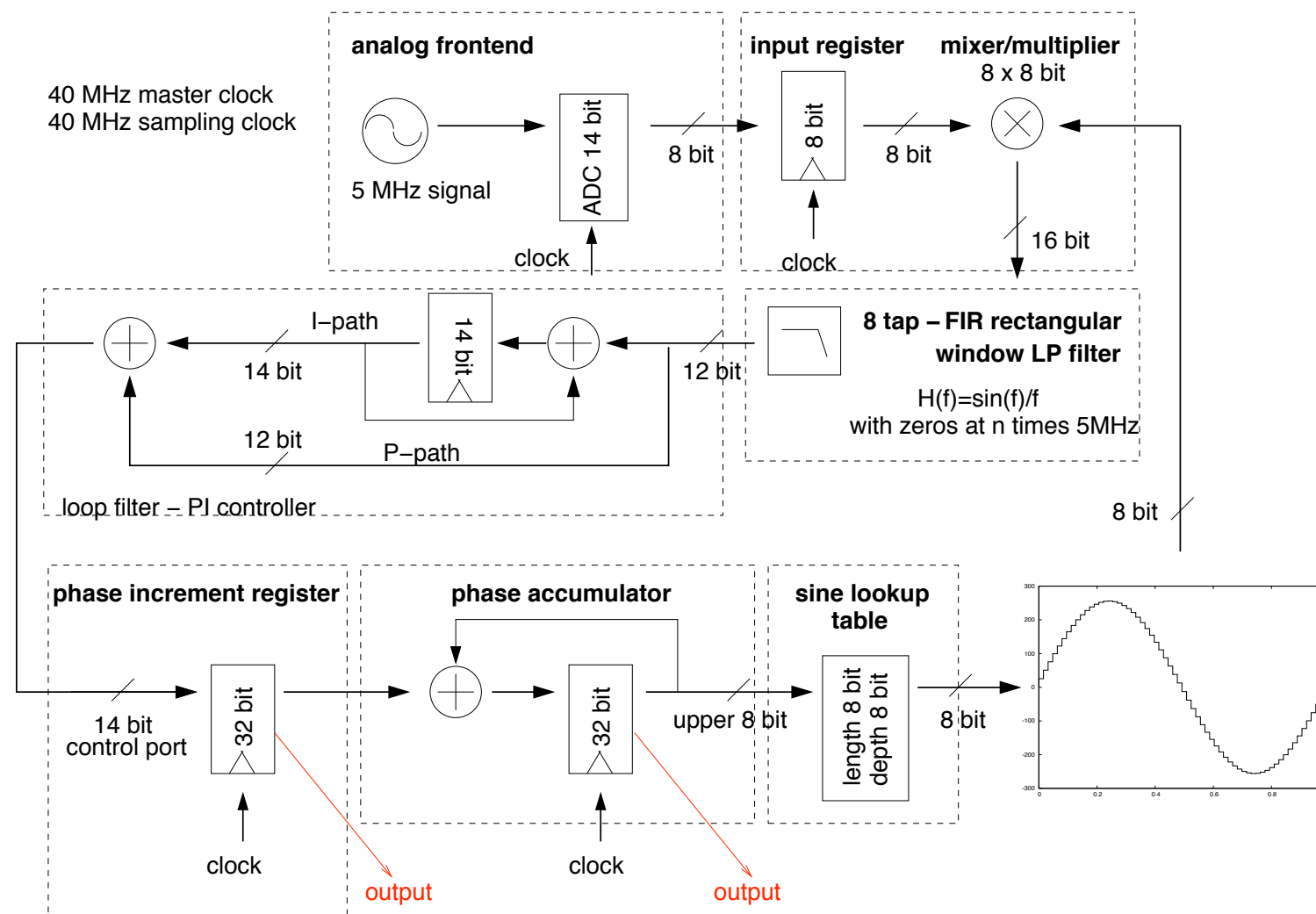
PRN codes

simple generation
with shift registers:
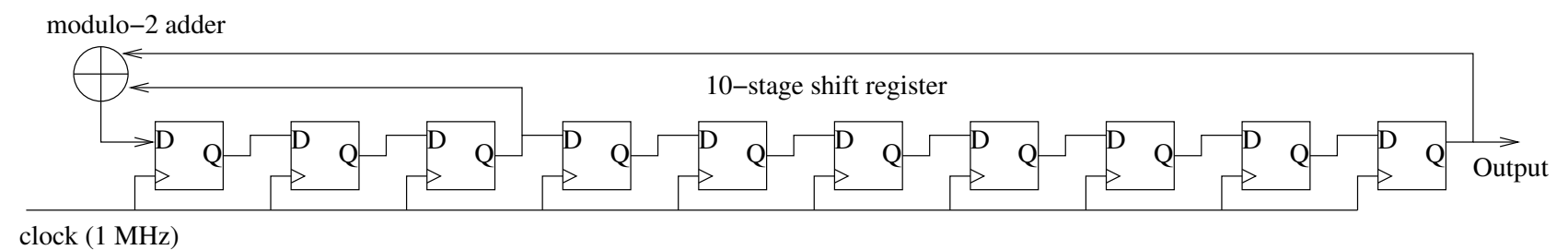
spectrum below
shot noise level:

sharp peak in
autocorrelation:

PRN demodulator

Both data transfer and inter-spacecraft ranging will be implemented by a weak spread spectrum (pseudo-random) modulation of the laser light. The basic pseudo-random code provides timestamps used for ranging and clock synchronization. Data bits are added by flipping the sign of the modulation.

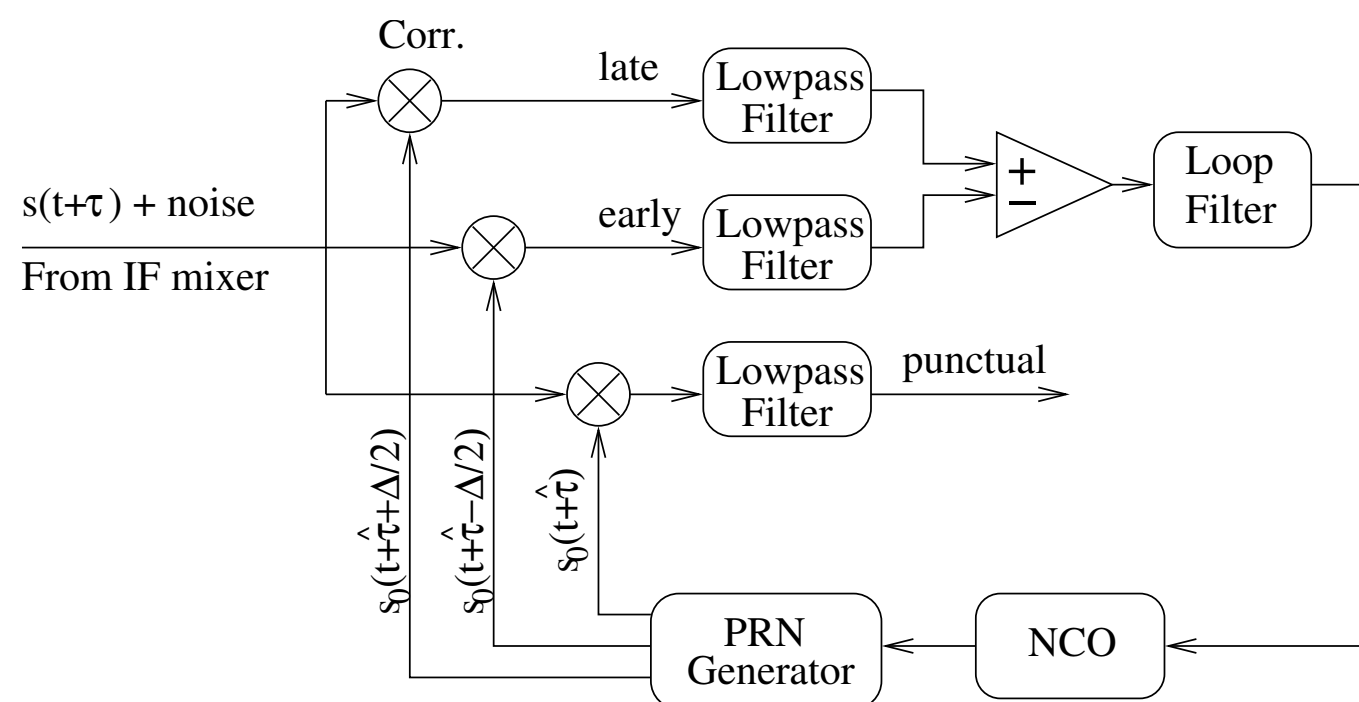Almost standard delay-locked-loop

Normally, data rate < code rate

Here:
chip rate $1\ldots 2\,$MHz,
data rate $100\ldots 400\,$kHz,
code length e.g. $3\,$kHz $\leftrightarrow 100\,$km,

code phase shift has zero DC average

needs demonstration with low-level optical signals and drifting carrier frequencies.

Ranging techniques

For TDI to work, the absolute distance between the spacecraft needs to be continuously known to better than 20 m accuraccy, and the three master clocks on the three spacecraft need to be synchronized to better than 100 ns.

The PRN correlation peak serves as timestamp, containing the clock offset and travel time.

Sending time-tagged messages back and forth between two spacecraft via the optical data link is straightforward in principle, but intricate in detail due to relativistic corrections and the desired symmetry between three identical spacecraft.


$$\Delta t = t2' - (t1 - t3)/2$$
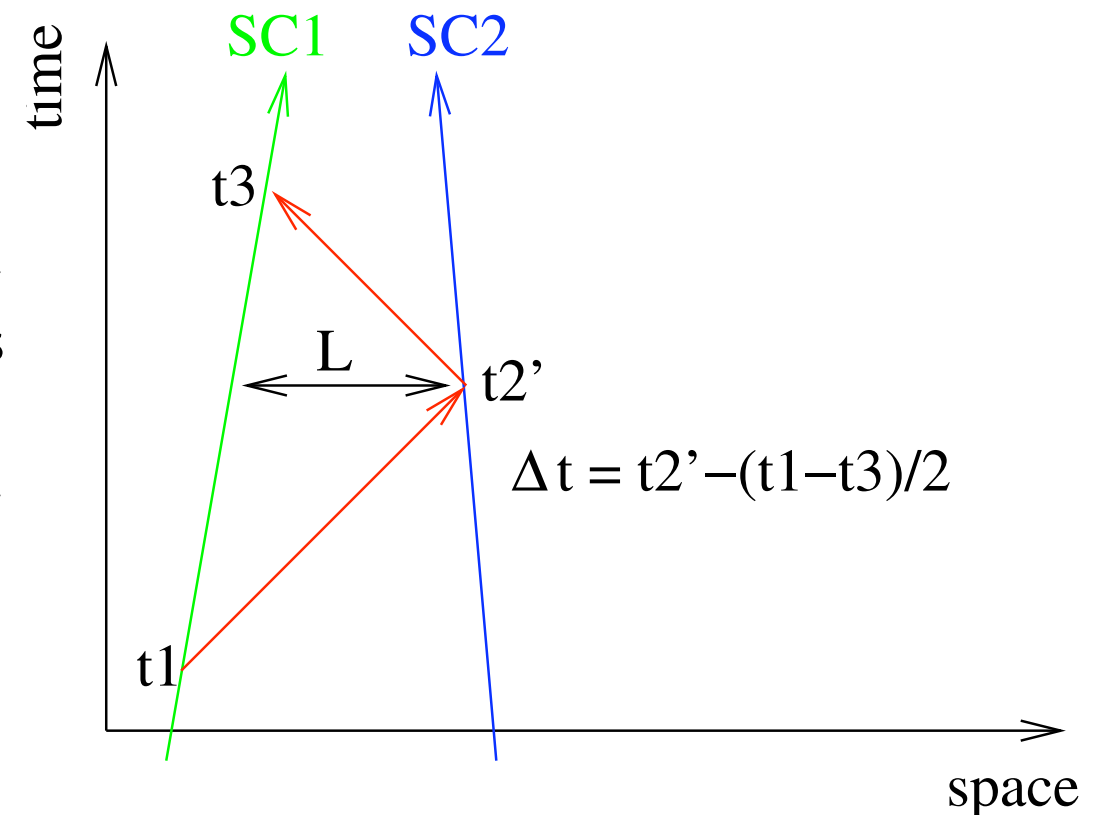
Accuracies better than 1 m should easily be reachable, and could be further improved by integrating the Doppler shift in a Kalman filter.

# Point-ahead angle

- Within the 33 s round-trip travel time, the remote satellite moves.

- in-plane 6 μrad constant, out-of-plane $\pm$6 μrad within 1 year.

- angle is magnified $\approx 80\ldots100$ times by telescope $\Rightarrow$ 500 μrad!

- actuator is in receive beam $\Rightarrow$ longitudinal noise $\lesssim$ pm required.

- no fast error signal for closed-loop operation $\Rightarrow$ high dead-reckoning feedforward precision required.
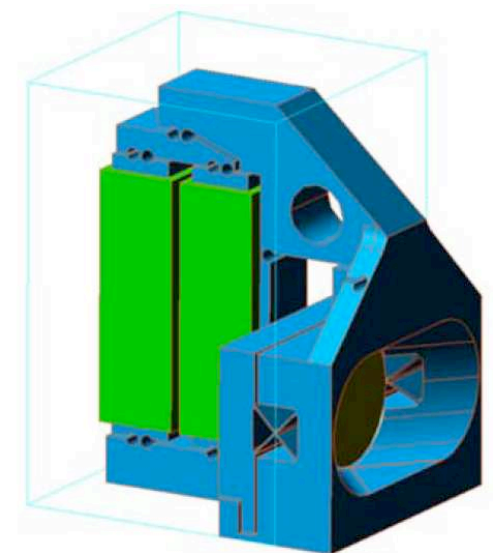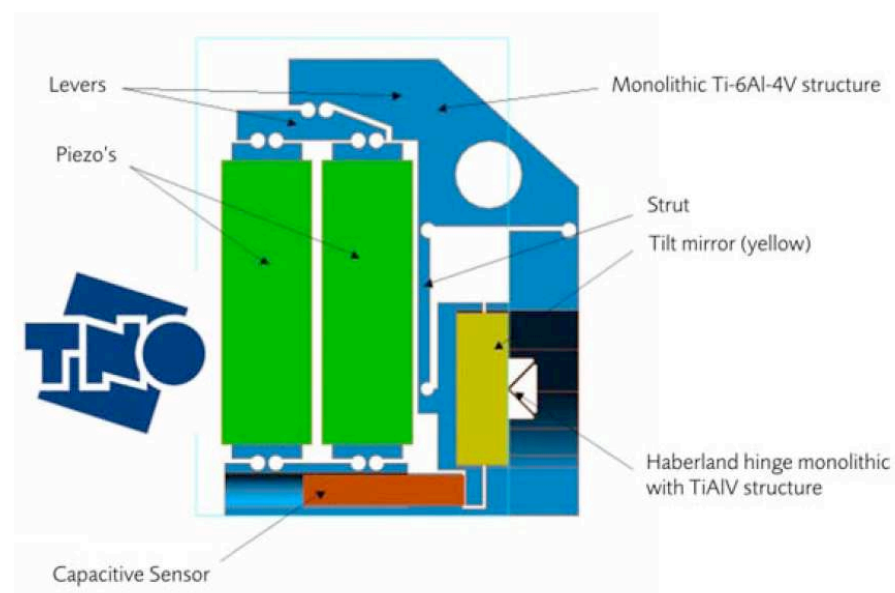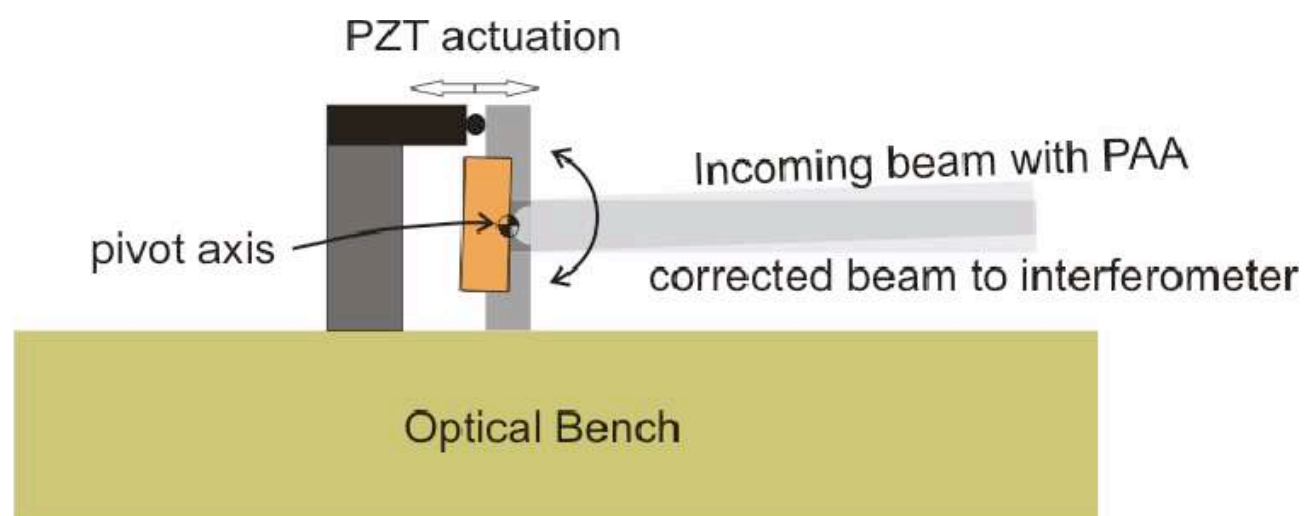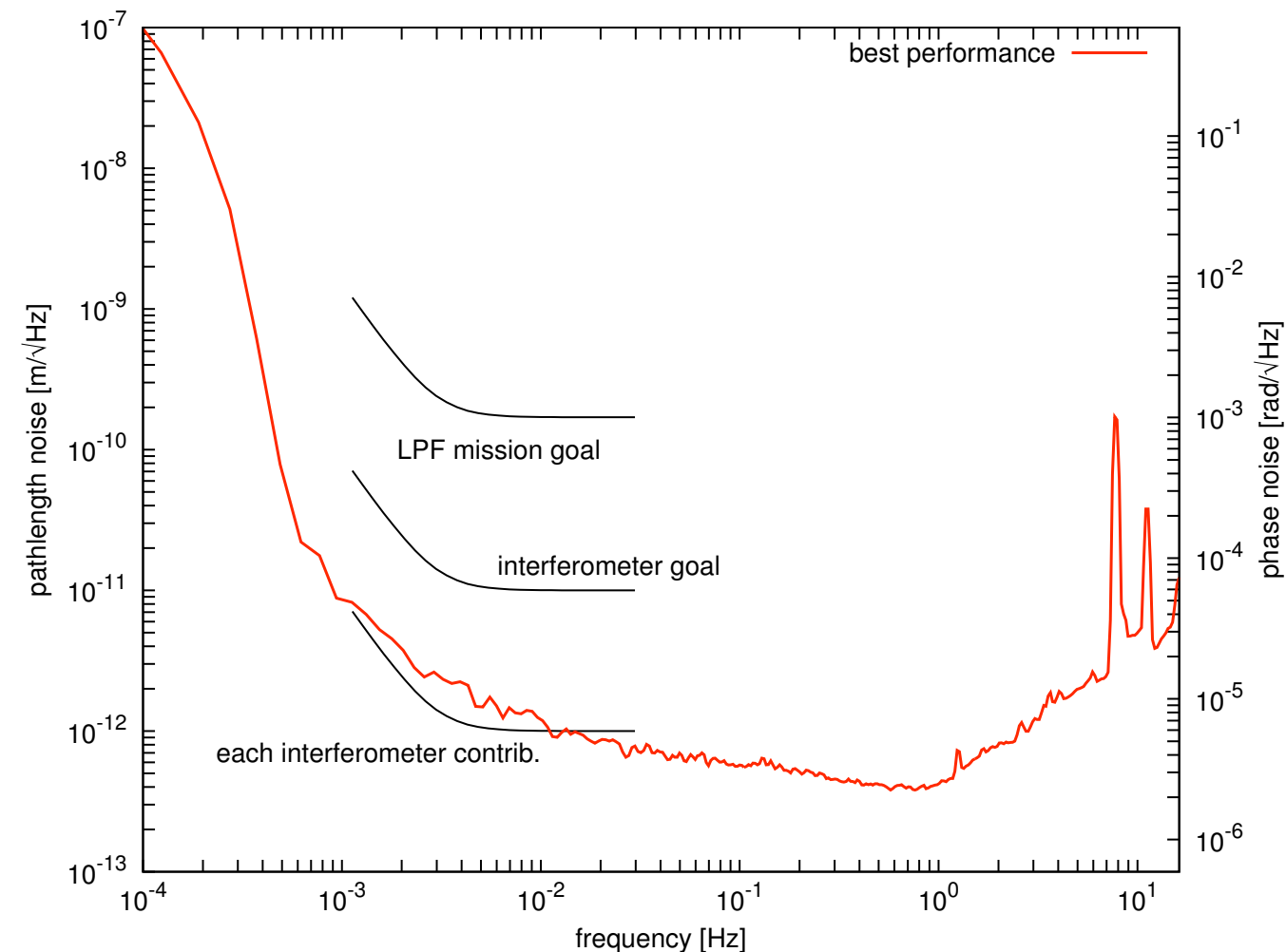
Local interferometry: heritage from LISA Pathfinder
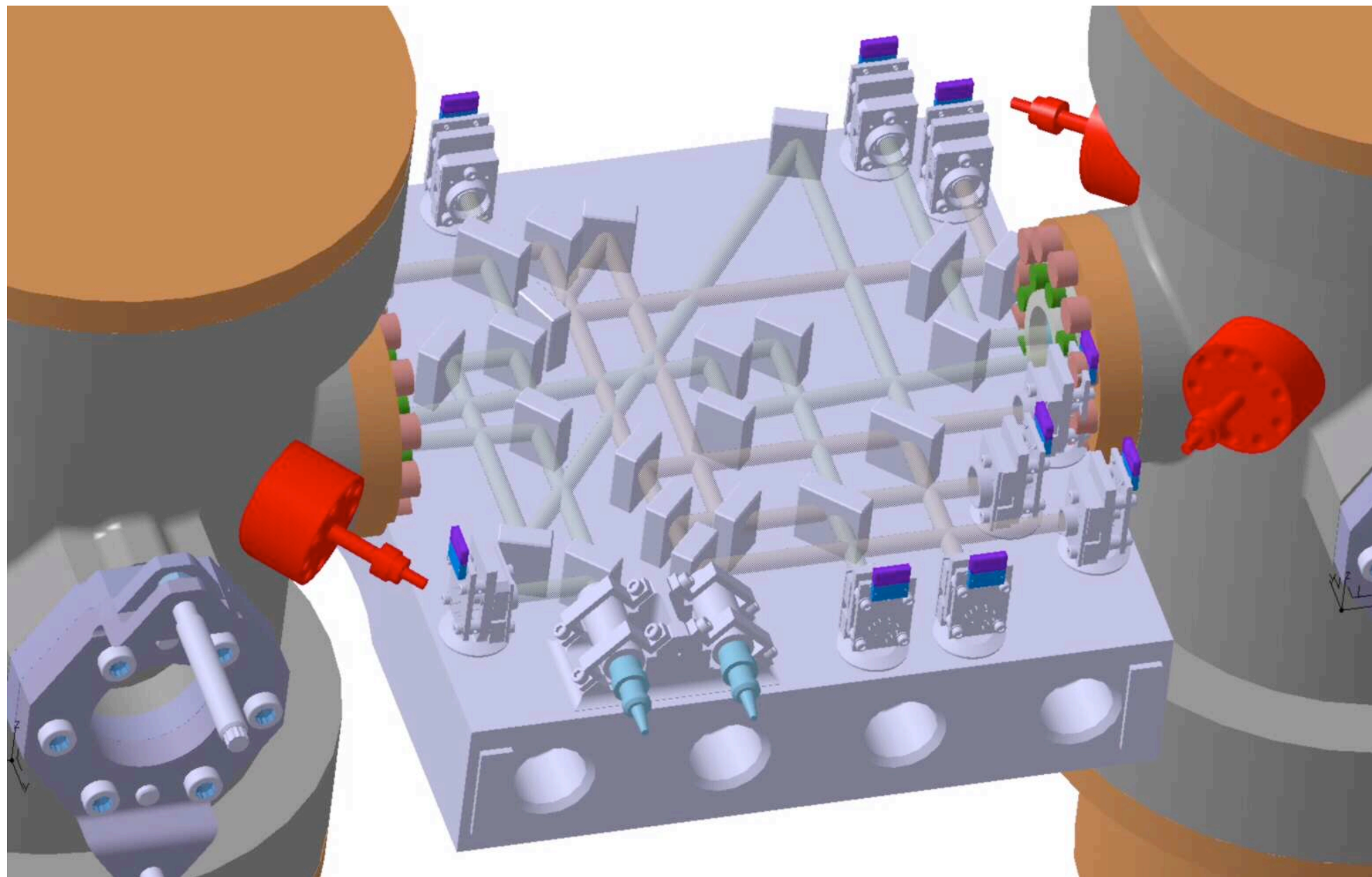
LTP interferometer performance

The noise is now well below spec thanks to OPD stabilization, amplitude stabilization, frequency stabilization and a improved FPGA-based phasemeter
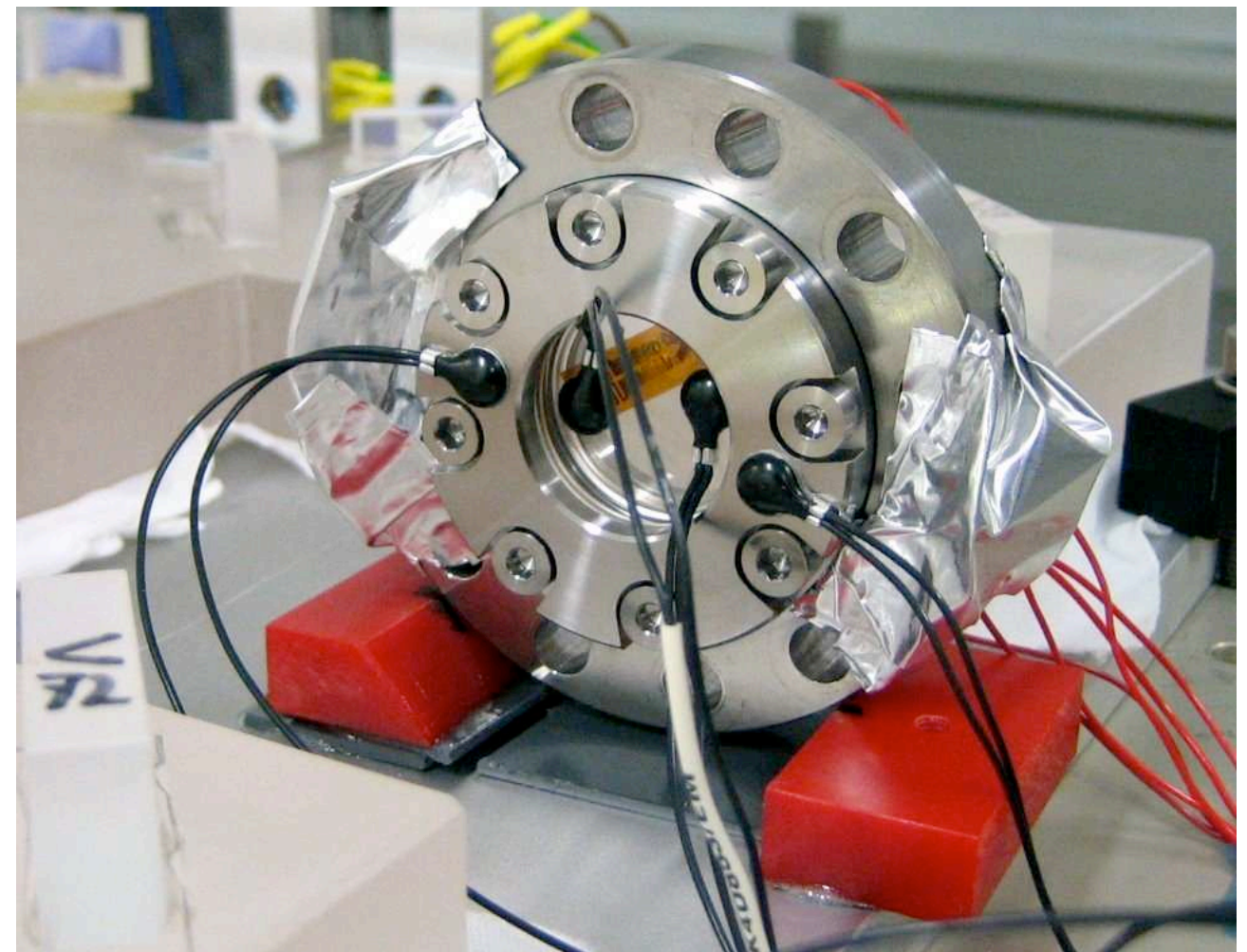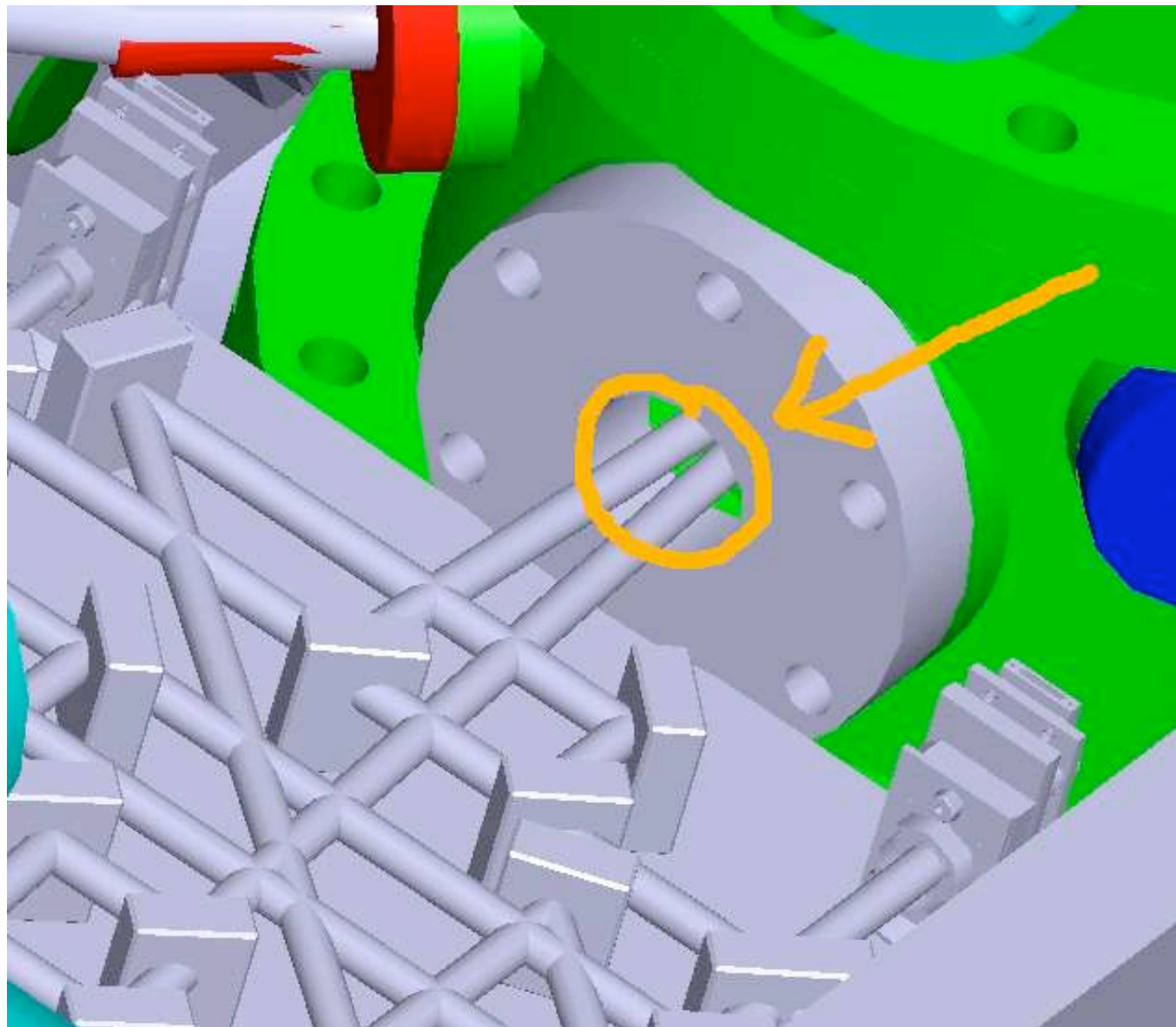
The LTP interferometer already reaches the LISA requirements and could be used as local readout.

Contra: more complex than baseline (AOM modulators, extra reference ifo and phasemeter)
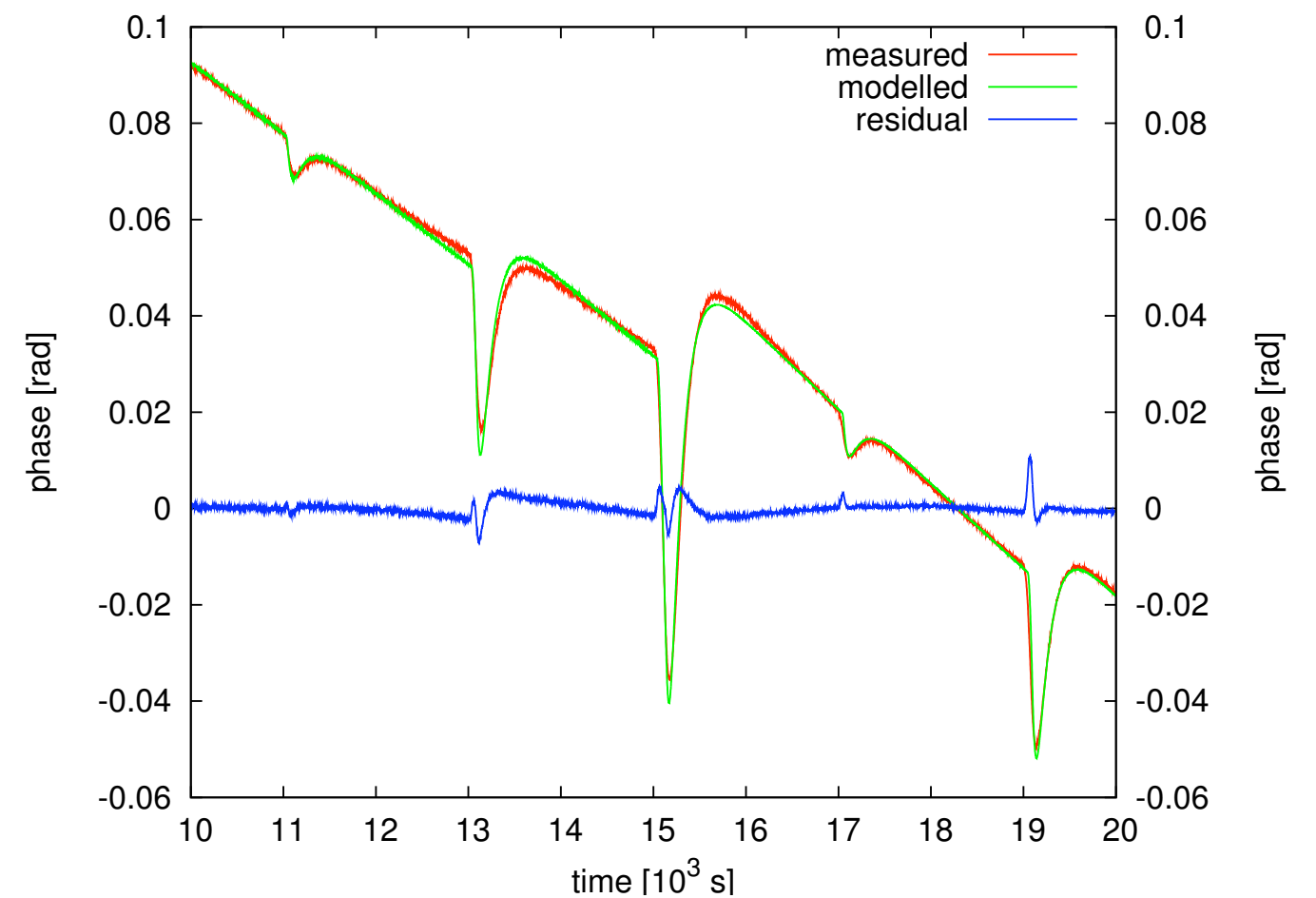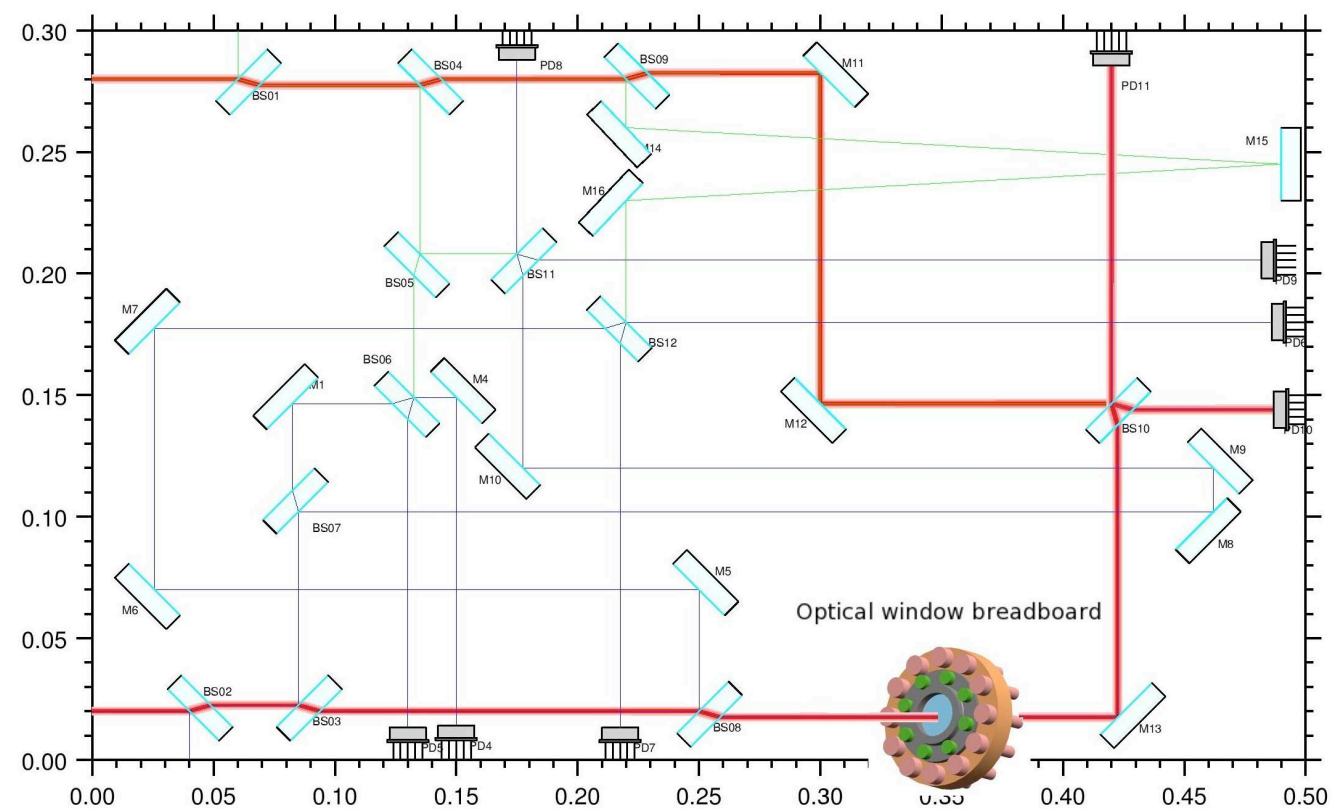Pro: Will be flown on LPF.

Optical window testing

We have tested prototype optical windows from athermal glass (Ohara S-PHM52).
That glass was chosen for its small FOM $\mathrm{d}n/\mathrm{d}T + (n-1)\alpha = 0.59\,\mathrm{ppm/K}$.
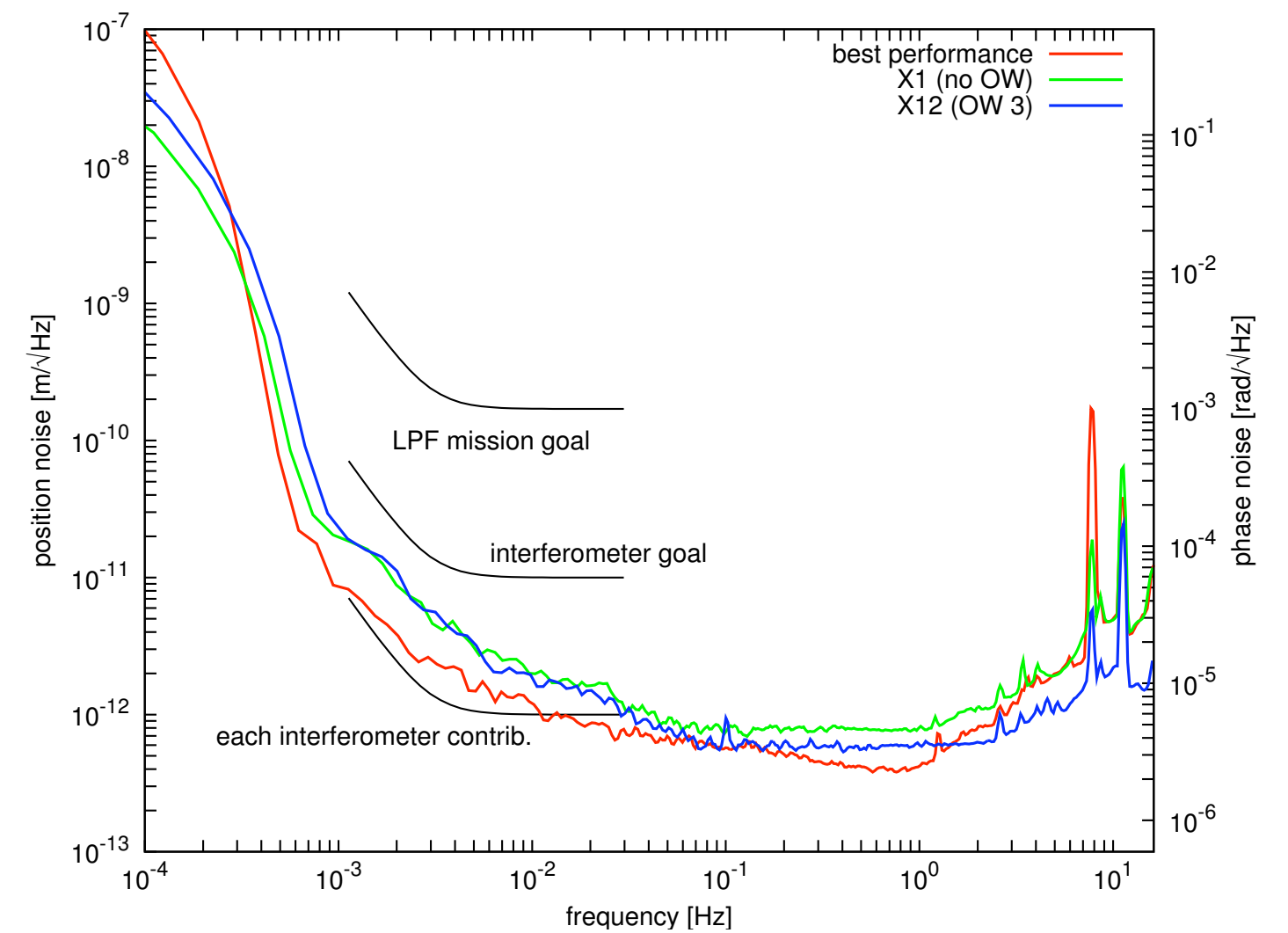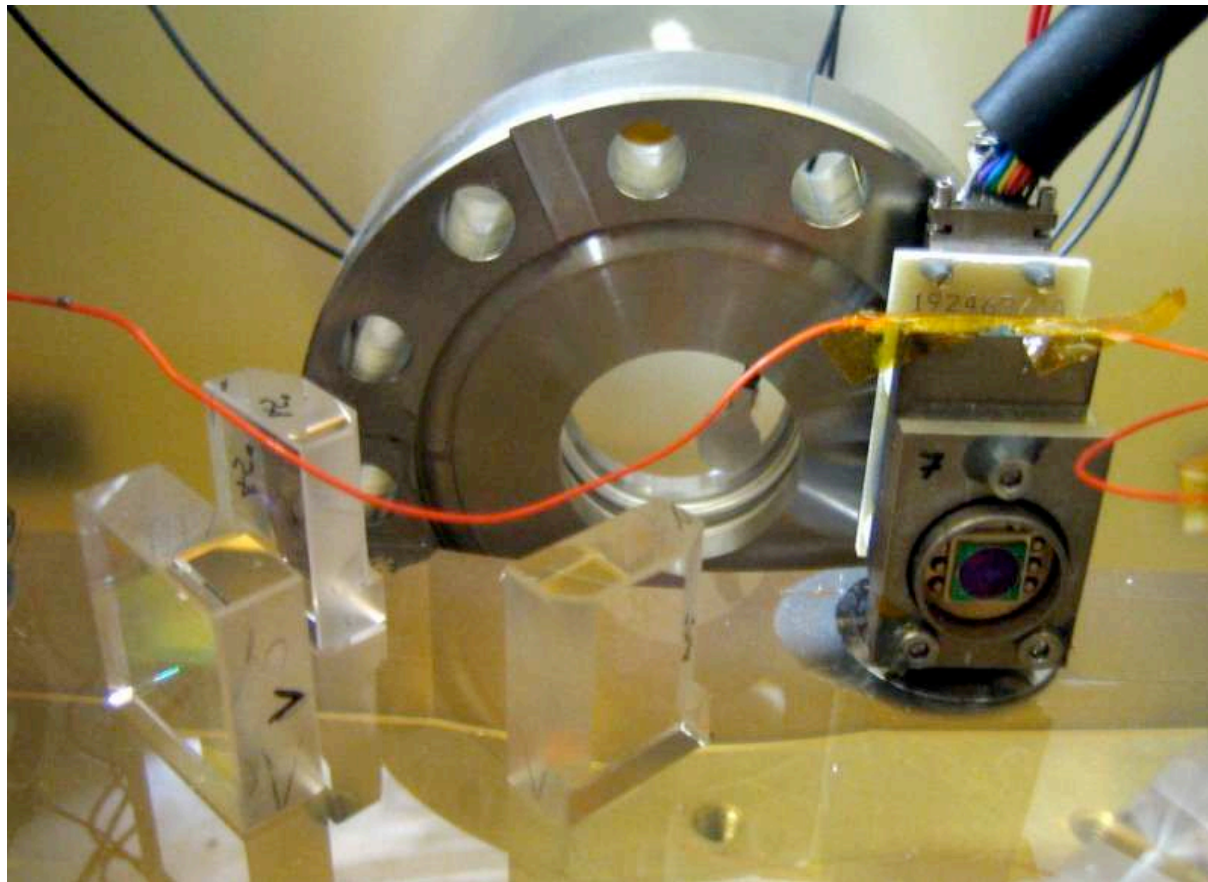
Optical window thermal tests

– dn/dT effect consistent with predictions: 0.6 ppm/K → 22 mrad/K single pass

– total thermal effects including mount modelled: 100 mrad/K single pass

– resulting requirement on thermal stability: $1.2 \cdot 10^{-5}$ K/$\sqrt{\text{Hz}}$ at 3 mHz

Stability measurements with optical window

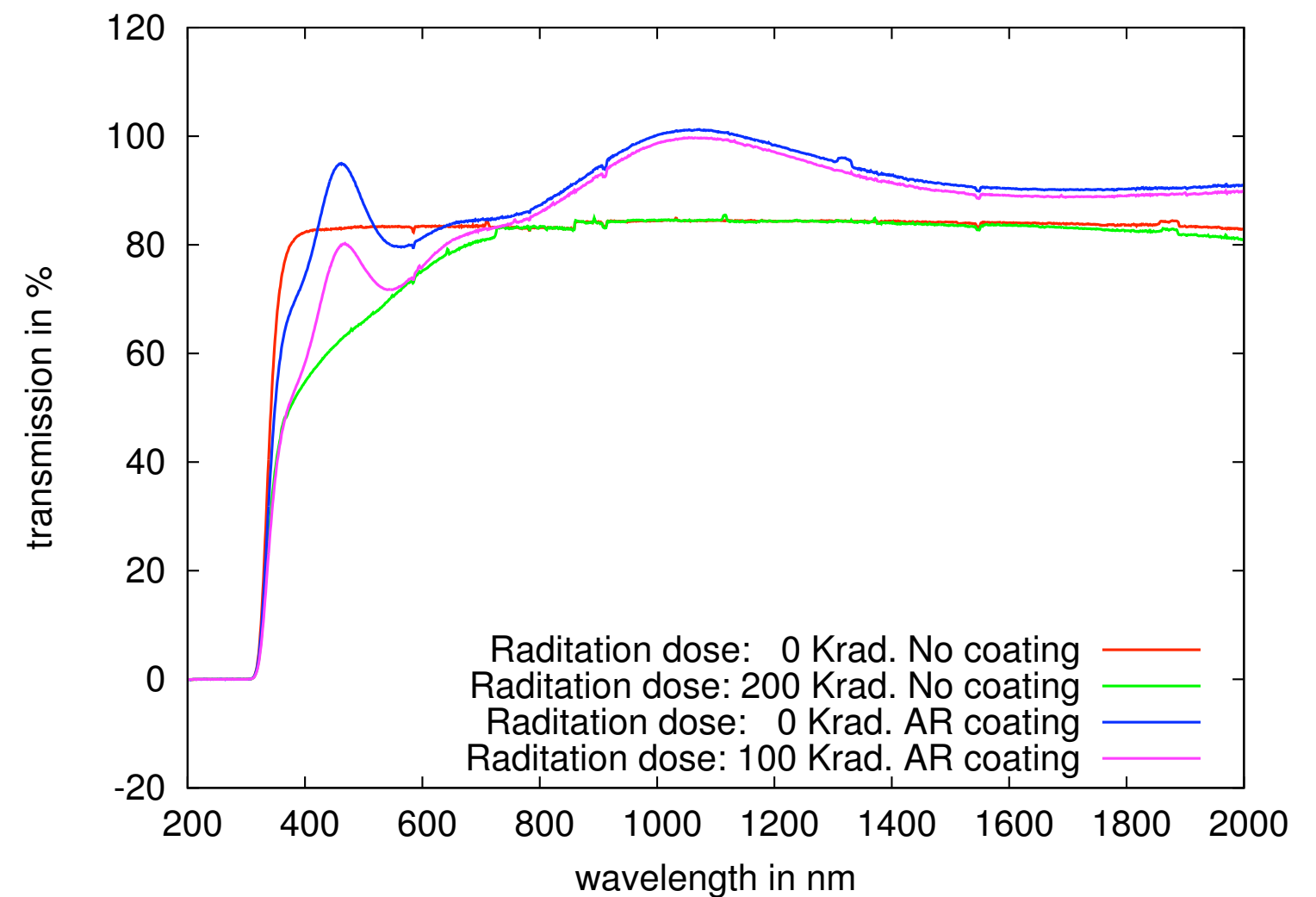
We have mounted the optical window in the OB EM and seen no significant increase in the pathlength noise in the LTP bandwidth.

Optical window radiation tests

Sample windows have been irradiated with 30 MeV protons up to 200 krad.

At 200 krad, they turn brown, which does, however, not affect the transmission at 1064 nm.
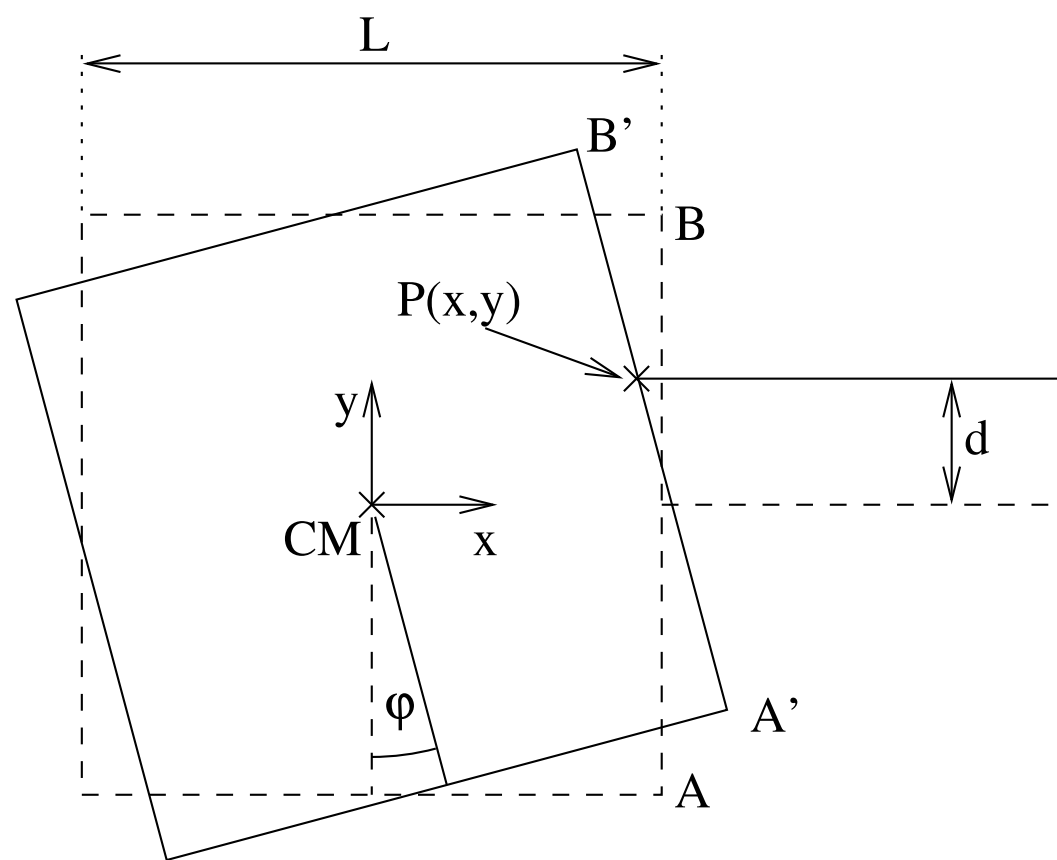
At radiation levels expected for LTP, the effect is negligible.

Alignment jitter → longitudinal coupling

One important from LPF is the importance of tilt coupling. In LISA, the optical axis of the telescope must pass through the TM center of mass to avoid coupling of spacecraft jitter.

A similar effect occurs in LTP when the test mass jitters:

- any offset couples rotational noise into longitudinal measurement.
- with $500\,\mathrm{nrad}/\sqrt{\mathrm{Hz}}$ of TM jitter, the probe beam needs to hit the TM within $\pm 1\,\mu\mathrm{m}$ of the nominal position. This is unrealistic.
- By using the $<10\,\mathrm{nrad}/\sqrt{\mathrm{Hz}}$ alignment measurements, this can be relaxed to $\pm 50\,\mu\mathrm{m}$: not trivial, but possible.
- Approach: stabilize the jitter as good as possible, subtract the remainder
- subtraction of DWS signals is equivalent to weighting the 4 quadrants with factors near 1

Voltage reference tests: results with moderate temperature stabilization

Stable voltage are needed in several places:
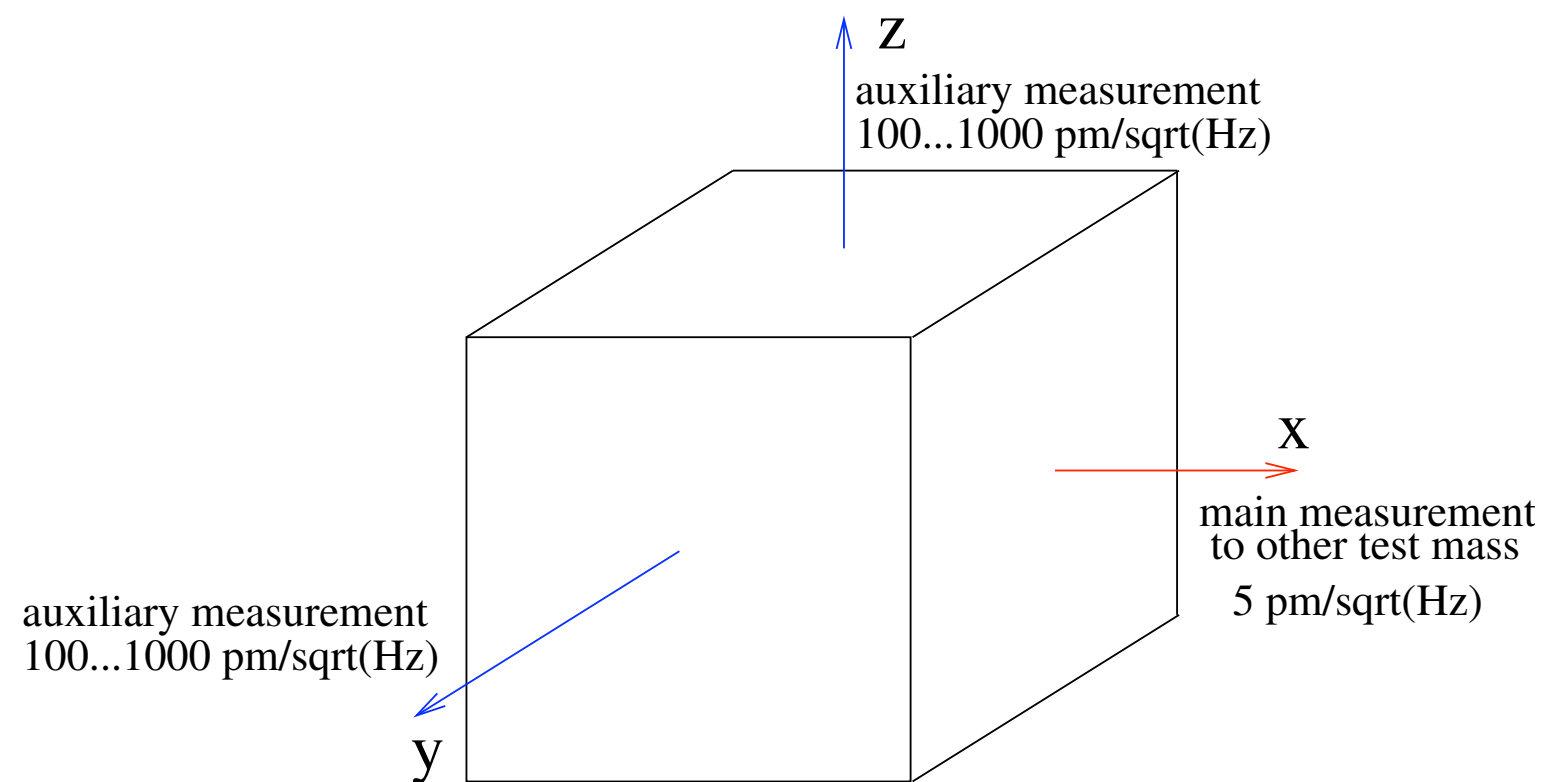
− Laser power stabilization

− Piezo drivers for PAA and reference cavity

− Photodiode bias

− Test mass capacitive actuators
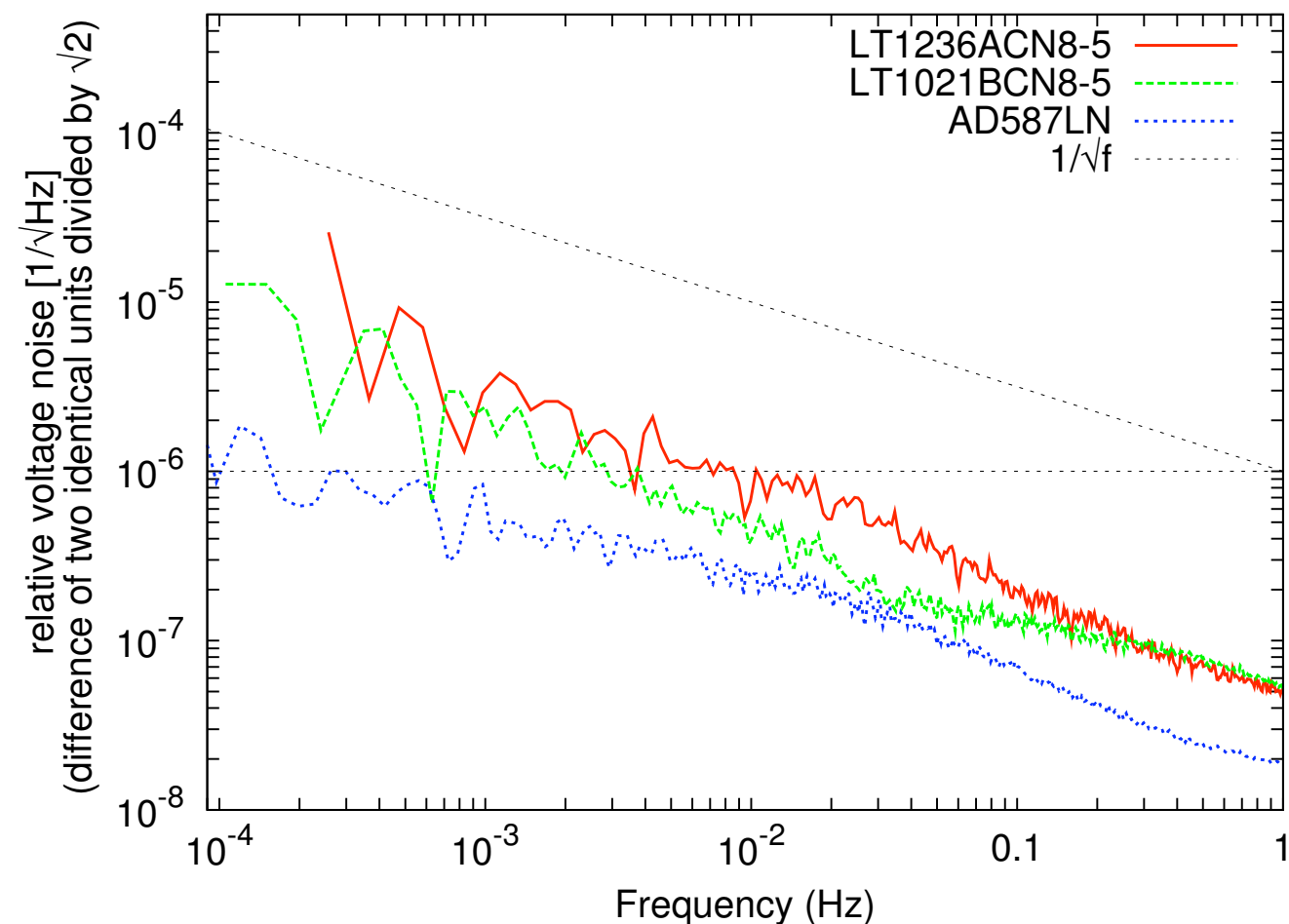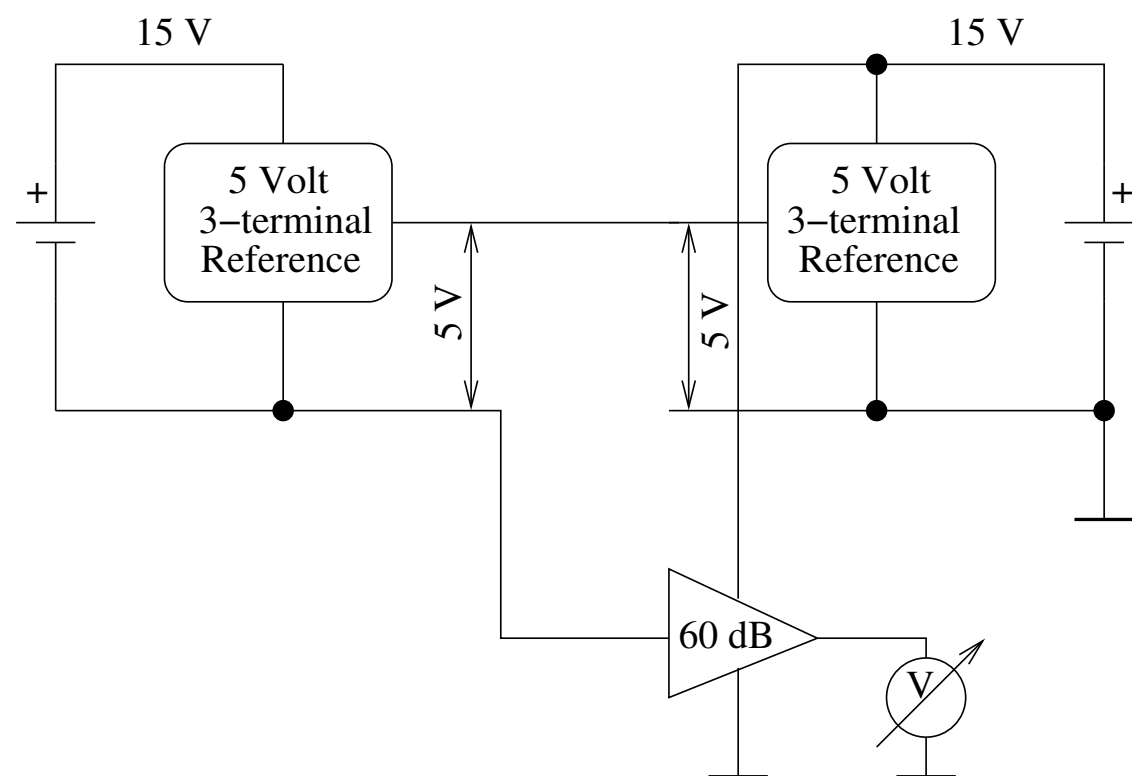
The AD587LN with temperature stabilization almost reaches $10^{-6}/\sqrt{\mathrm{Hz}}$ down to $0.1\,\mathrm{mHz}$.

Optical readout in y and z

z
auxiliary measurement
100...1000 pm/sqrt(Hz)

x
main measurement
to other test mass
5 pm/sqrt(Hz)

auxiliary measurement
100...1000 pm/sqrt(Hz)

y

- 'x' is the main interferometer axis; an optical readout with $\approx 5\,\mathrm{pm}/\sqrt{\mathsf{Hz}}$ is needed in any case.

- 'y' and 'z' are nominally insensitive. Due to various couplings and for the drag-free operation, they must also be sensed.

- The electrostatic readout delivers $\approx 2000\,\mathrm{pm}/\sqrt{\mathsf{Hz}}$. It will be there in any case, since the electrodes are needed for actuation and for redundancy.

- An extra optical readout in 'y' and 'z' with $100\ldots500\,\mathrm{pm}/\sqrt{\mathsf{Hz}}$ would ease requirements on other subsystems and provide redundancy.

- Optical readout in y and z is not presently the baseline, but kept as option.

Position-sensitive detector from Napoli:
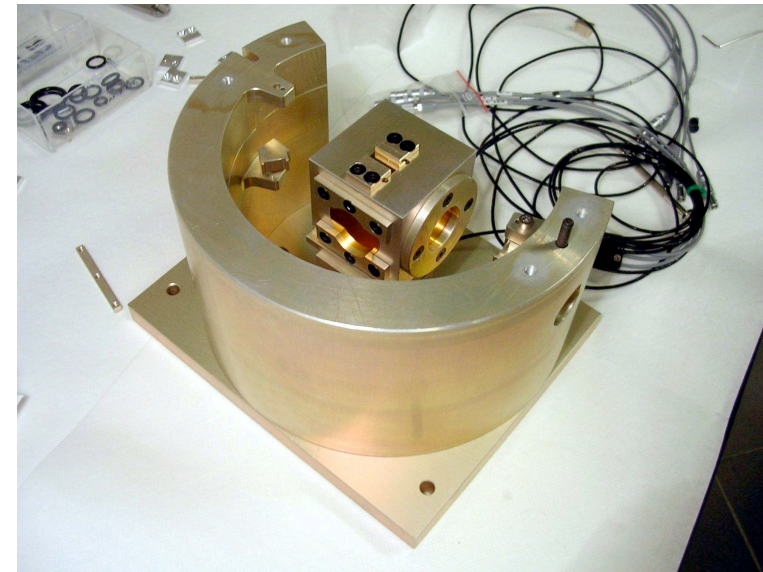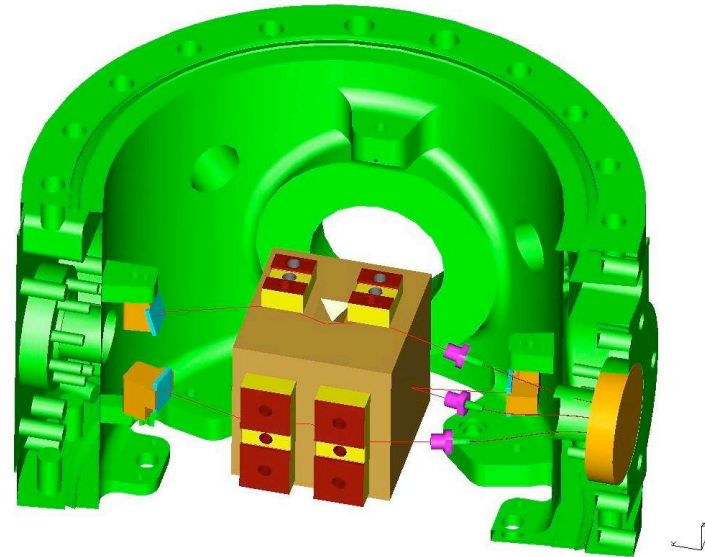
Polarising homodyne I-Q-interferometer from Birmingham:
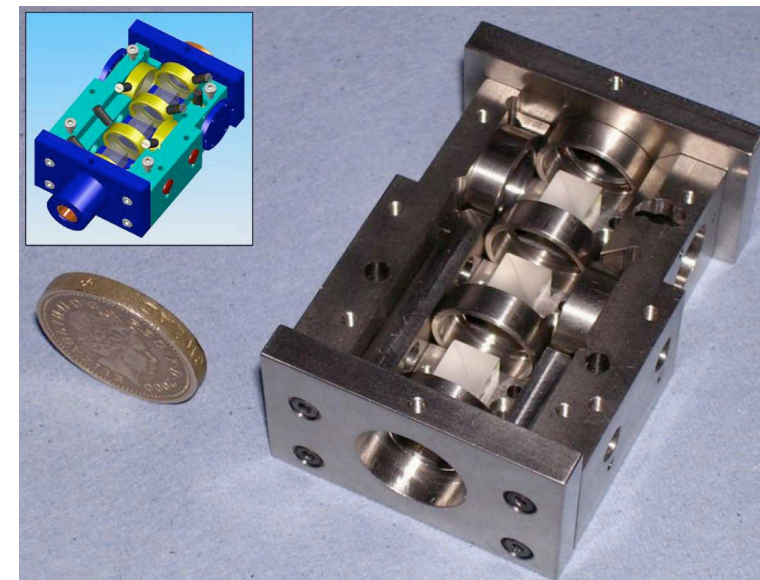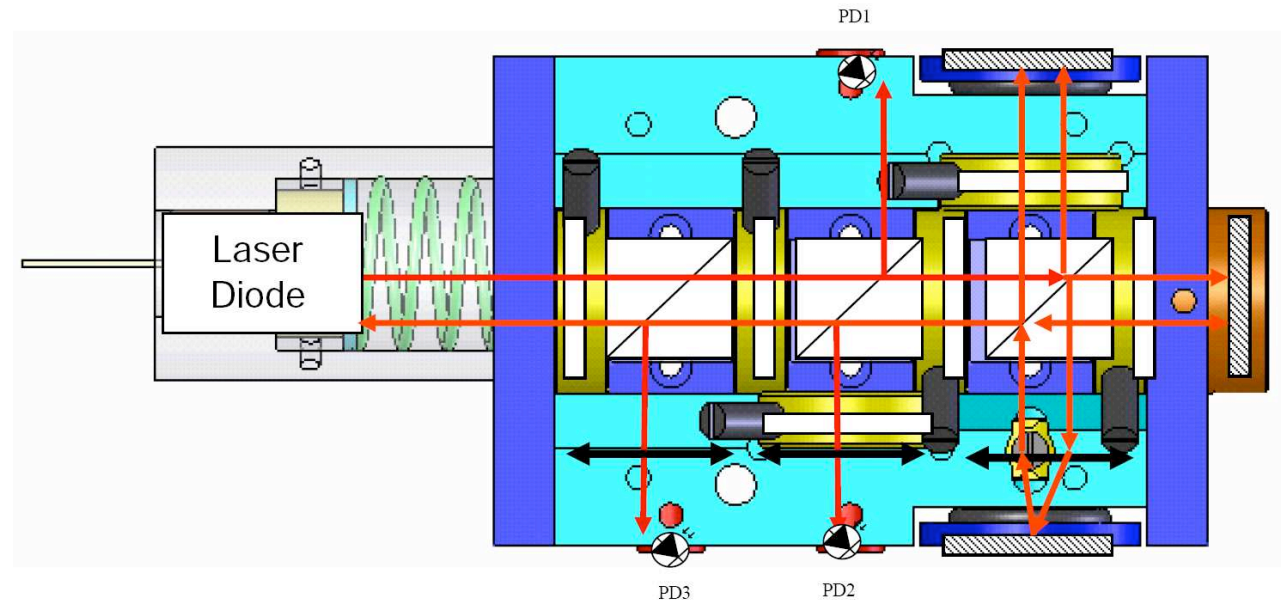
Interferometers are also under development in Berlin in Hannover.
see talk by C. Speake this afternoon and posters.

Conclusion

- There is now a consistent baseline architecture for the interferometry, agreed by both ESA and NASA.

- Development of LISA pathfinder has proved far more beneficial than merely verifying the acceleration noise.

- Some items need further development, but no showstopper has been found.

- If some item should prove impractical, options of the architecture are available.

- Now is an excellent time for universities and institutes to get involved and look at the open questions!

- LIST working group 2 (interferometry) is open to everyone and welcomes new participants! Contact: Guido Müller or G. Heinzel.

some possible tasks for universities and institutes:

– telescope defocus calculations (so far: WG2 subgroup)

– focus adjustment mechanism (**none**)

– telescope material investigation: CFRP, SiC,. . . (UoF, Birmingham)

– telescope: readout of primary ↔ secondary distance (**none**)

– phase fidelity of EOM / laser amplifier (AEI)

– laser redundancy switch mechanism (**none**)

– PAA mechanism incl. readout (**none**)

– fiber back link reciprocity (AEI, Glasgow?, UoF?)

– beam dumps (**none**)

– phasemeter (JPL and several others)

– photodetectors incl. preamplifiers (AEI, ANU?)

– TDI/arm locking simulations (JPL, UoF, APC)

– tunable cavity (GSFC?)

– fiber couplers (Glasgow)

– polarizing optics performance (**none**)

– iodine stabilization (GSFC, APC)

(from LIST working group 2: contact Guido Müller or Gerhard Heinzel)